IS HEXAGONAL FLOW JUST A SUPERPOSITION OF ELLIPTIC AND TRIANGULAR FLOWS ?

E. Zabrodin

in collaboration with

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University of Oslo and Moscow State University

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OUTLINE

I. Description of anisotropic flow in relativistic heavy ion collisions:

(a) elliptic and triangular flows

(b) initial fluctuations and higher harmonics

II. HYDJET++ model (hydro + jets)

III. Jets influence on NCQ-scaling and $v4/(v2)^2$ ratio at RHIC and LHC

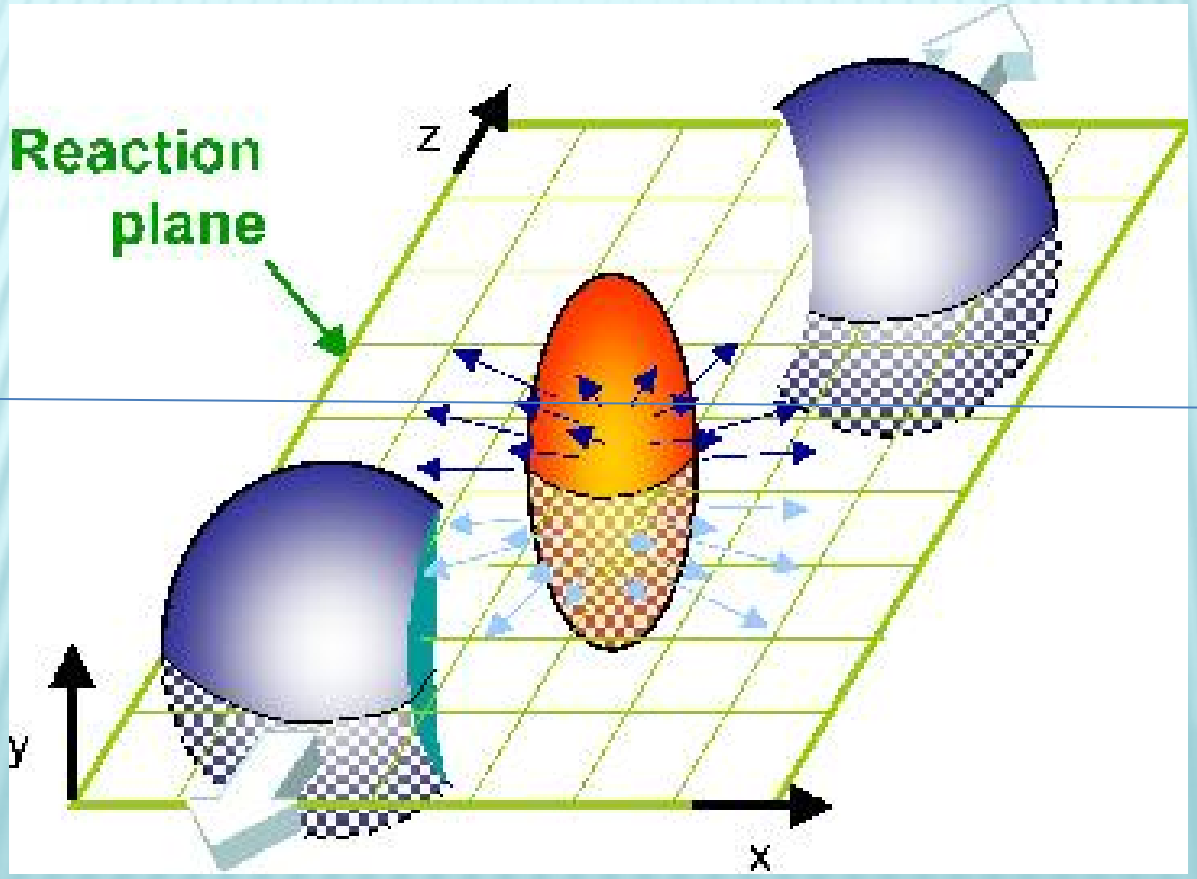
IV. Hexagonal flow v6

I. Description of anisotropic flow in relativistic heavy ion collisions

ANISOTROPIC FLOW

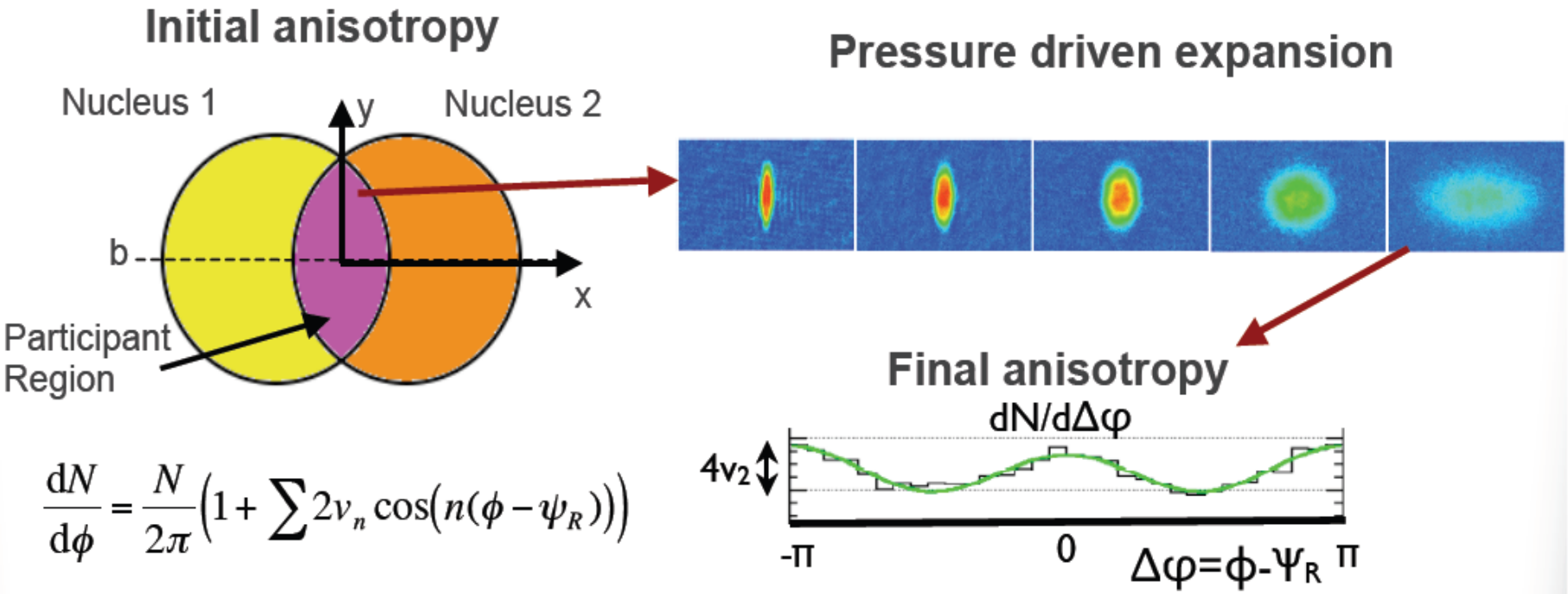
S.Voloshin and Y.Zhang, Z.Phys.C70 (1996) 665

$$\frac{dN}{d\varphi} = \frac{1}{2\pi}\left(1 + \sum_{n=1}^{\infty} 2v_n(p_t)\cos[n(\varphi - \psi_r)]\right)$$



ELLIPTIC FLOW

B. Alver, talk at Rencontres Ions Lourds (2010)

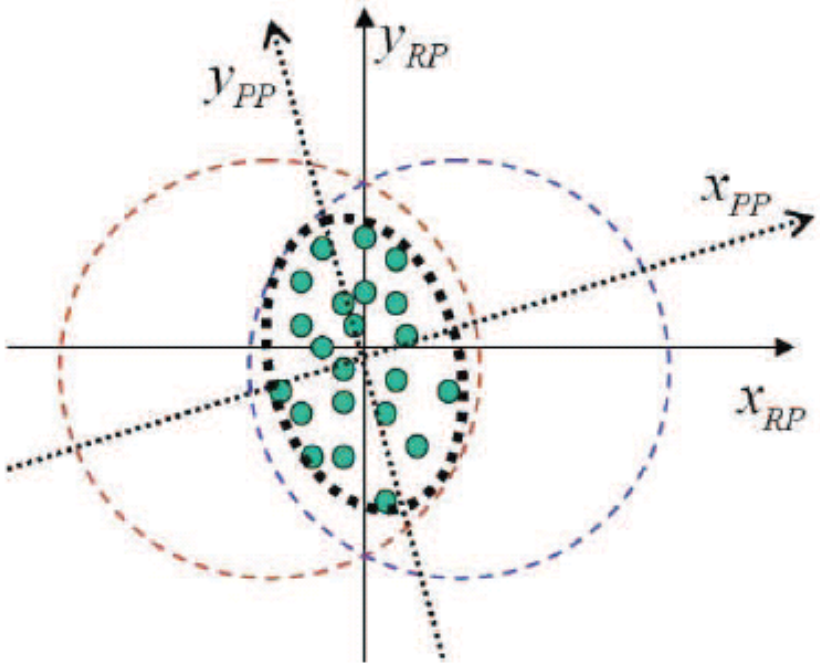


$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_R)\right)\right)$$

$$v_2 = \left\langle \cos\left(2(\phi - \psi_R)\right)\right\rangle \propto \varepsilon$$

Elliptic flow is quantified by the second Fourier coefficient (v_2) of the observed particle distribution

Eccentricity fluctuations



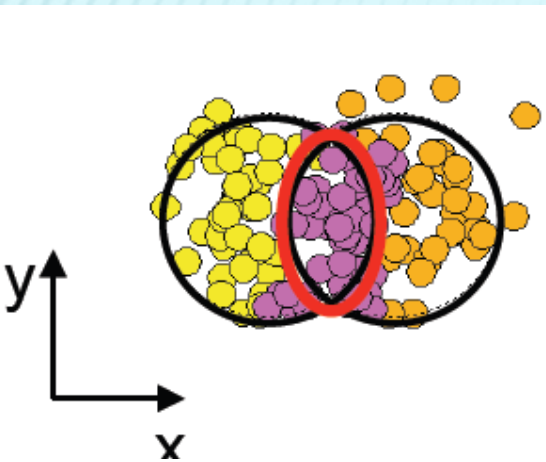
Depending on where the participant nucleons are located within the nucleus at the time of the collision, the actual shape of the overlap area may vary: the orientation and eccentricity of the ellipse defined by participants fluctuates.

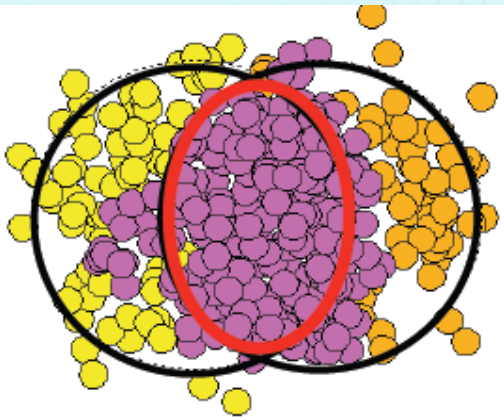
Assuming that v_2 scales like the eccentricity, eccentricity fluctuations translate into v_2 fluctuations

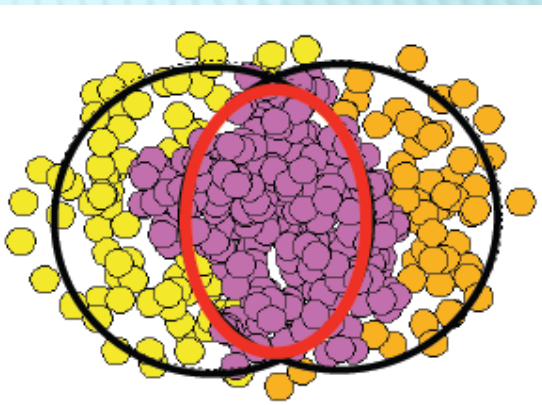
Eccenttricity fluctuation can be computed in MC Glauber model or derived from experiment by comparing different methods for flow calculation.

ECCENTRICITY

STANDARD



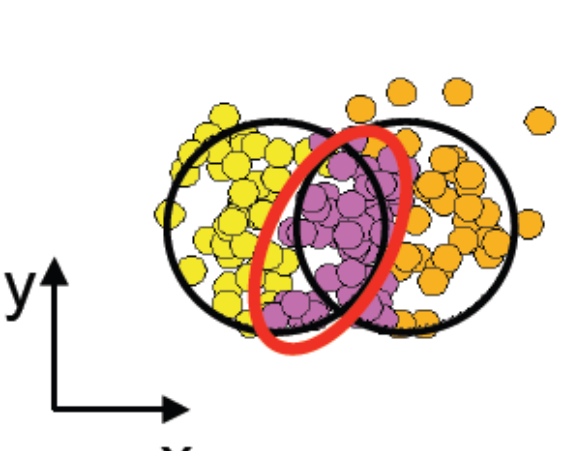


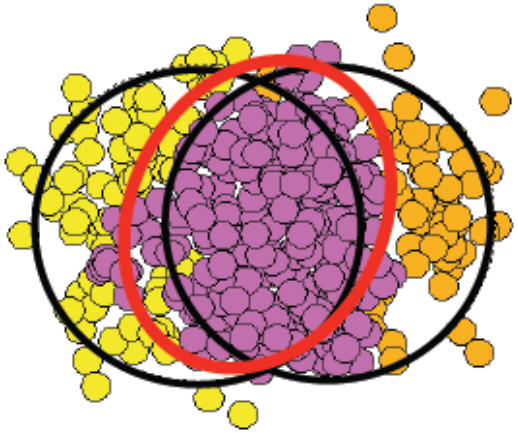


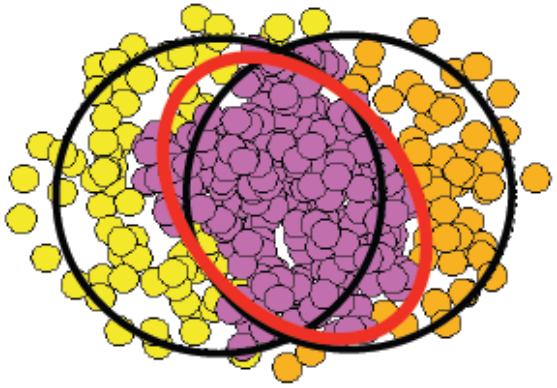
$$\varepsilon_{RP} = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

PARTICIPANT

$$\varepsilon_{part} = \frac{\sqrt{\left(\sigma_y^2 - \sigma_x^2\right)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$

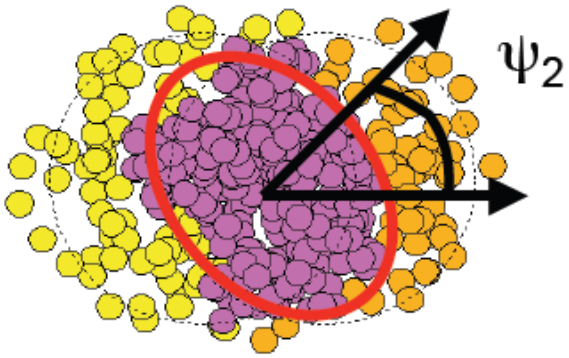


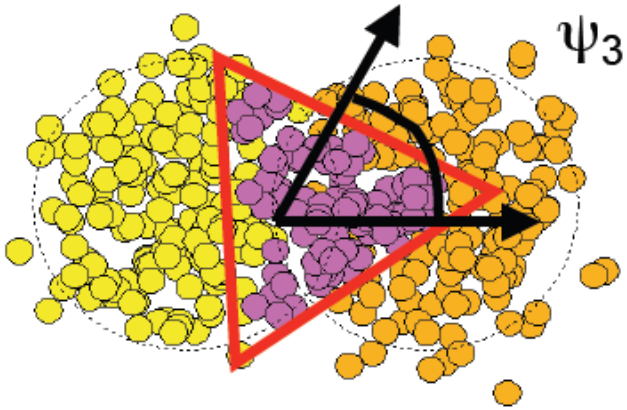


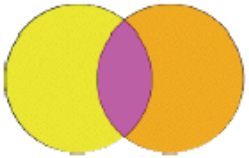


TRIANGULAR FLOW

B. Alver and G.Roland, PRC 81 (2010) 054905



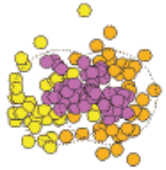




$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_R)\right)\right)$$

$$v_2 = \left\langle \cos\left(2(\phi - \psi_R)\right)\right\rangle$$

$$v_3 = 0$$



$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum 2v_n \cos\left(n(\phi - \psi_n)\right)\right)$$

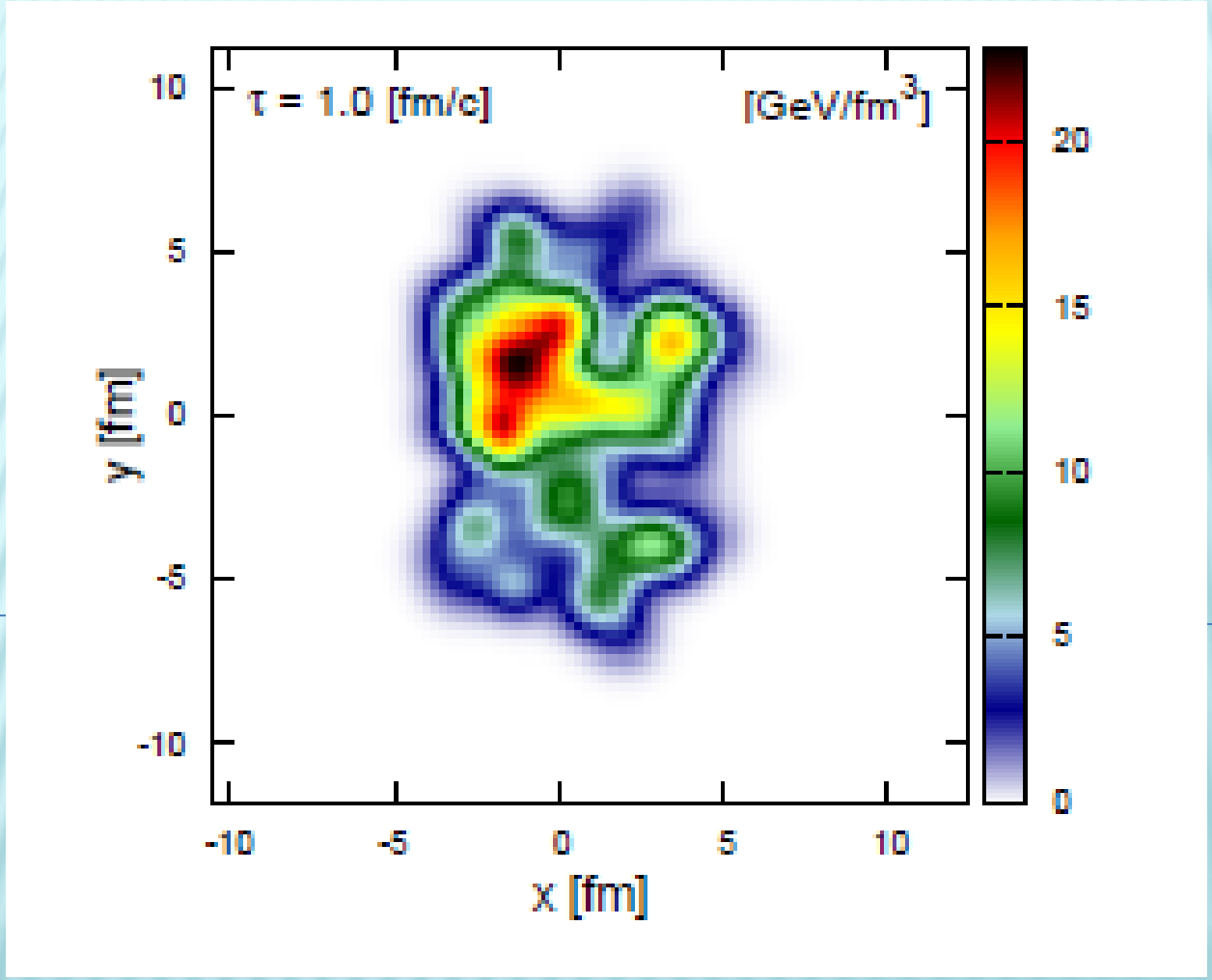
$$v_2 = \left\langle \cos\left(2(\phi - \psi_2)\right)\right\rangle$$

$$v_3 = \left\langle \cos\left(3(\phi - \psi_3)\right)\right\rangle$$

The triangular initial shape leads to triangular hydrodynamic flow

INITAL-STATE FLUCTUATIONS (example)

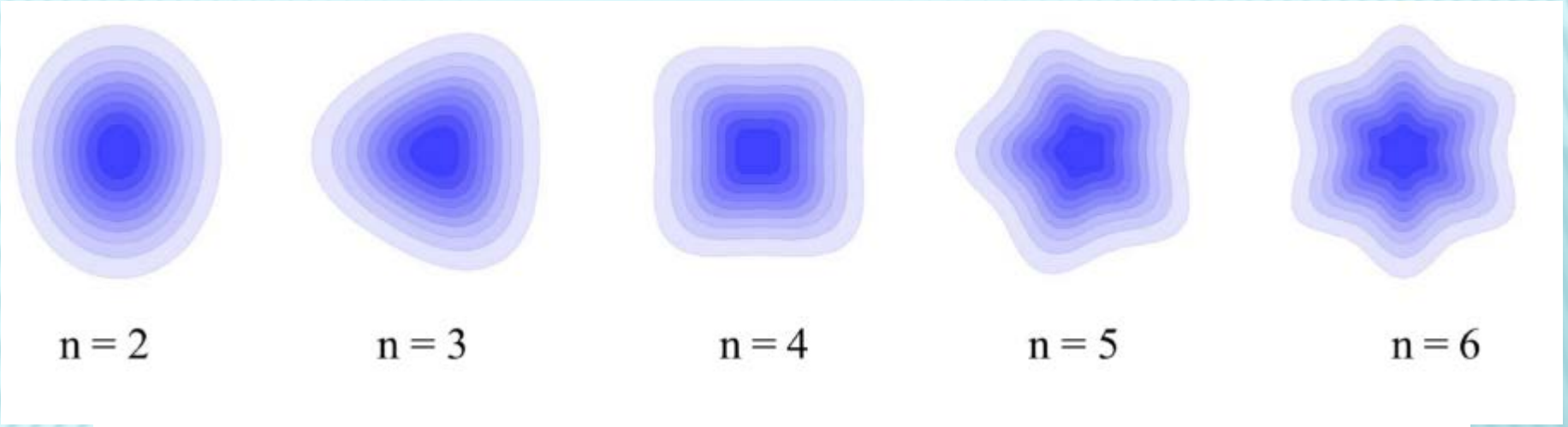
W.-L. Qian et al., arXiv: 1305.4673 [hep-ph]

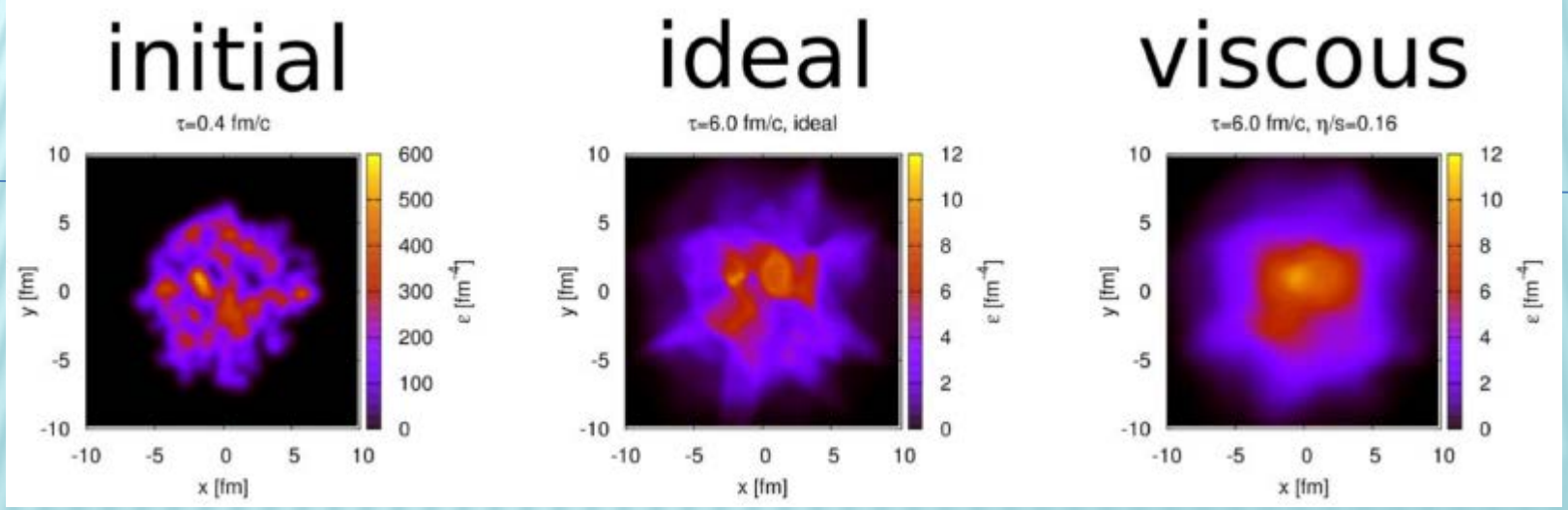


Energy distribution of a random NeXuS event

HIGHER FLOW HARMONICS

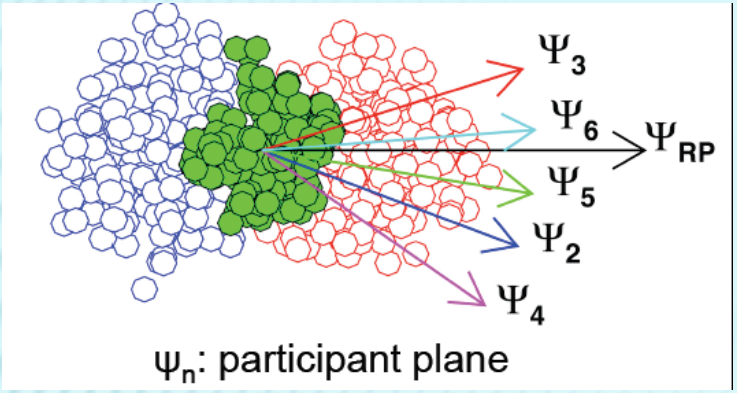
(from S. Petrushanko's talk)





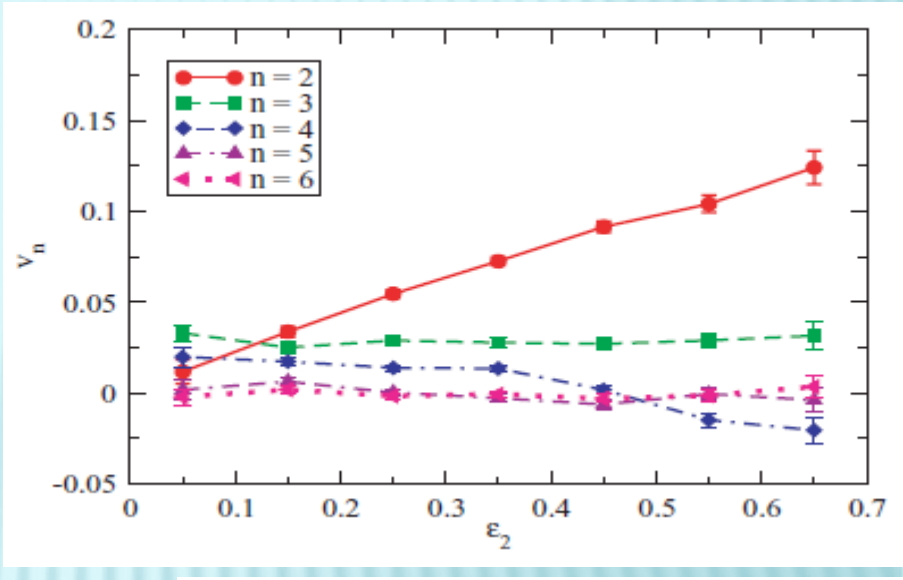
Non-zero high Fourier coefficients carry important information about the space-time evolution of the QCD-matter and initial fluctuations

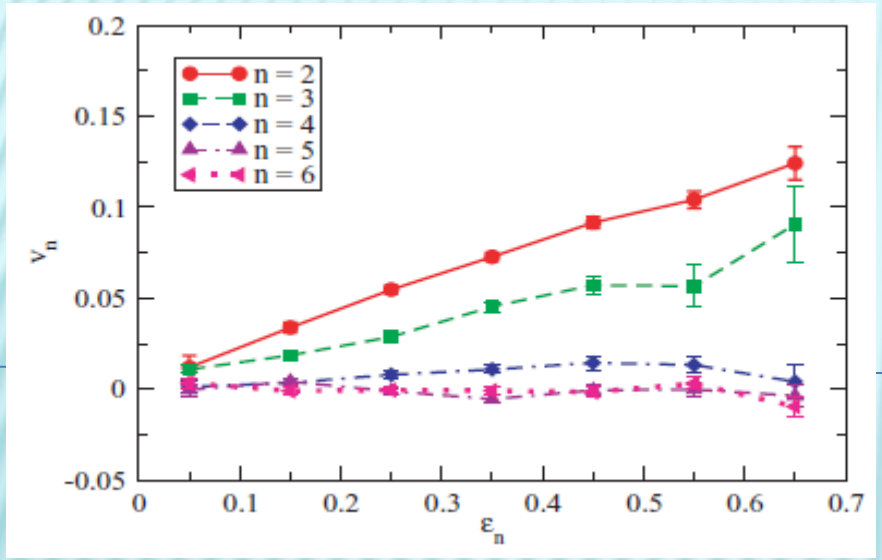
CROSS-TALK BETWEEN FLOW HARMONICS



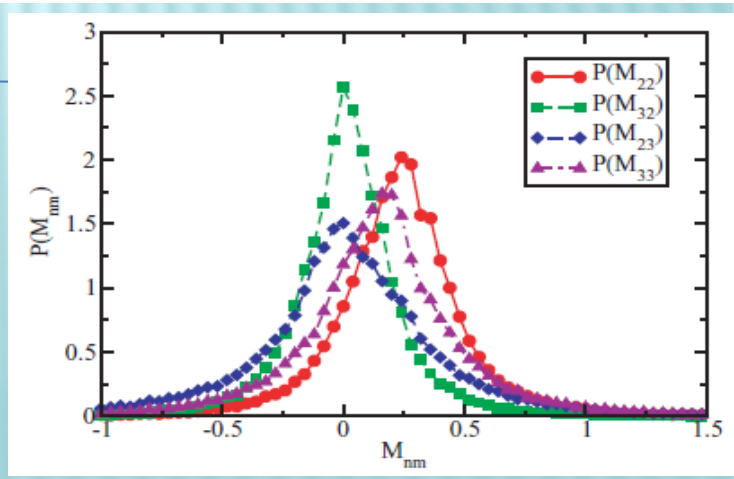
ψ_n: participant plane

G.-Y. Qin et al, PRC 82 (2010) 064903





$$\begin{pmatrix} v_2 \\ v_3 \end{pmatrix} = \begin{pmatrix} M_{22} & M_{23} \\ M_{32} & M_{33} \end{pmatrix} \begin{pmatrix} \epsilon_2 \\ \epsilon_3 \end{pmatrix}$$



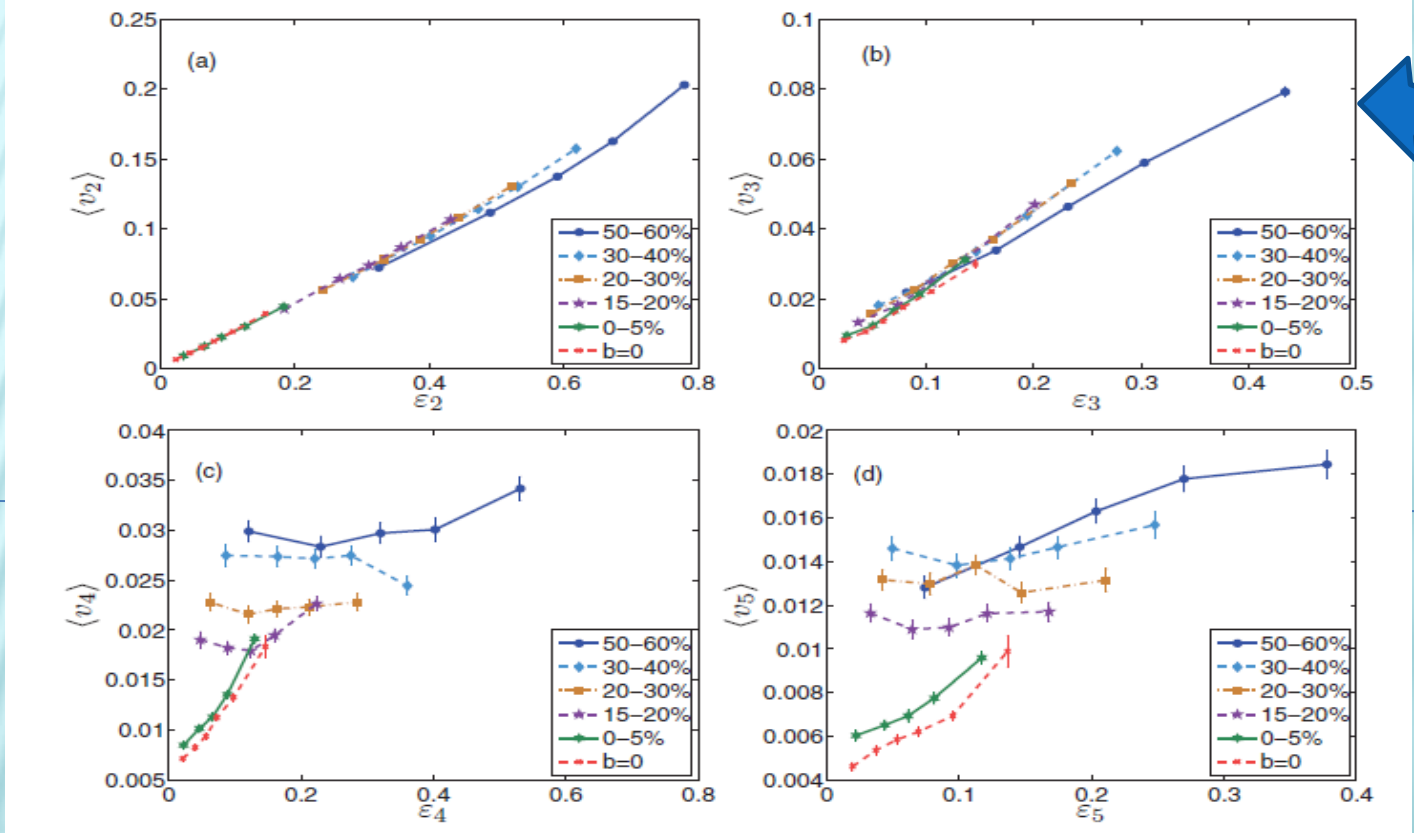
Only the first few flow harmonics of final-state hadrons survive after hydrodynamic evolution

CROSS-TALK BETWEEN FLOW HARMONICS

Z. Qiu and U. Heinz, PRC 84 (2011) 024911

$$\varepsilon_n\, e^{in\psi_n^{PP}} = -\frac{\int dx\, dy\, r^2 e^{in\phi}\, e(x,y)}{\int dx\, dy\, r^2\, e(x,y)}$$

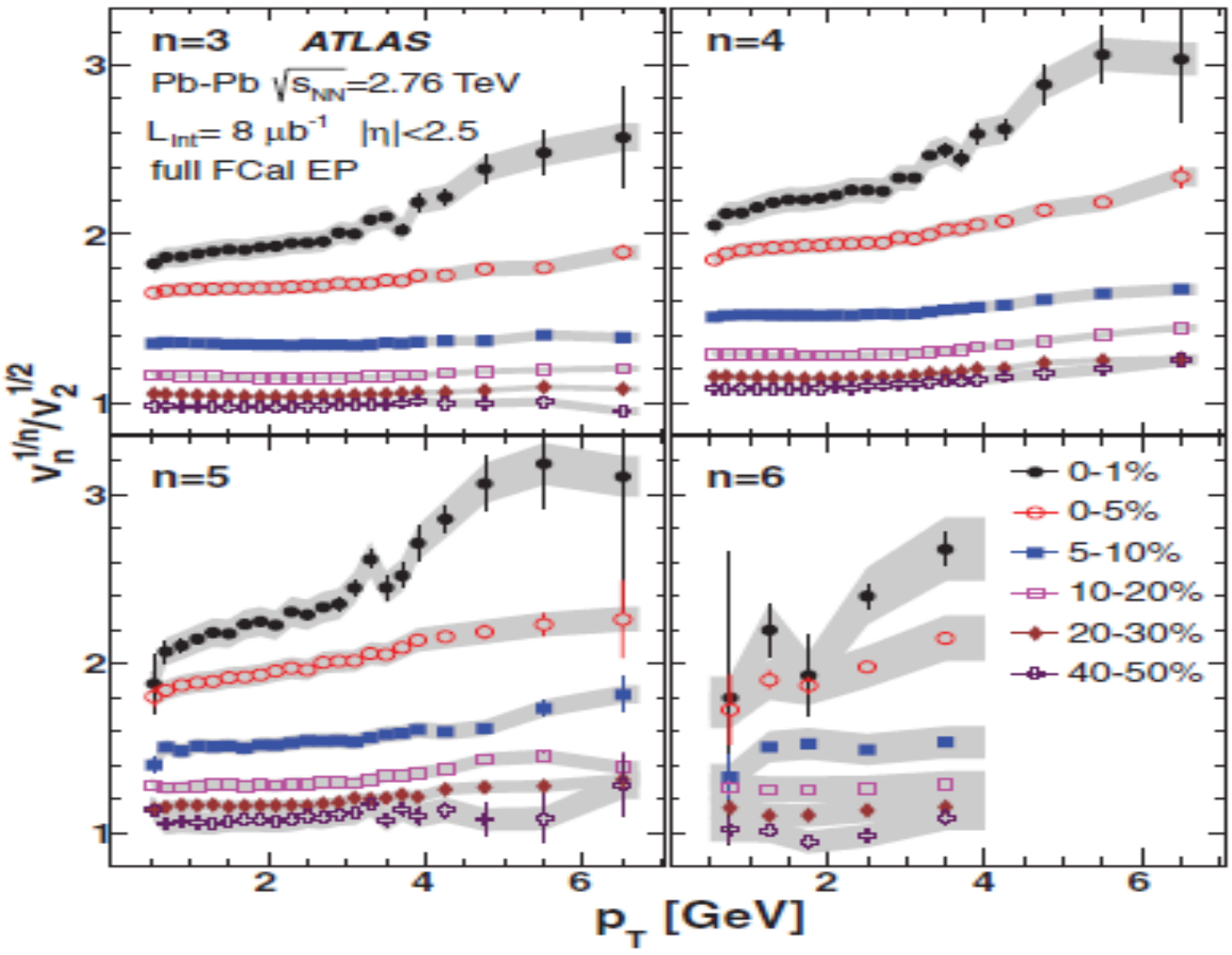
$$v_n(y, p_T)\, e^{in\psi_n^{EP}(y,p_T)} = \frac{\int d\phi_p\, e^{in\phi_p}\, \frac{dN}{dy\, p_T dp_T\, d\phi_p}}{\frac{dN}{dy\, p_T dp_T}}$$



(1) The basic response of v2 and v3 to eccentricities is approx. linear

(2) Higher flow coefficients show poor correlation with the eccentricities of the same order

SCALING OF HIGHER ORDER FLOW HARMONICS



ATLAS, PRC 86 (2012) 014907

J.-Y. Ollitrault :

$$V_n^{1/n} \simeq V_2^{1/2}$$

II. HYDJET++ =
FASTMS + HYDJET

HYDJET++ event generator

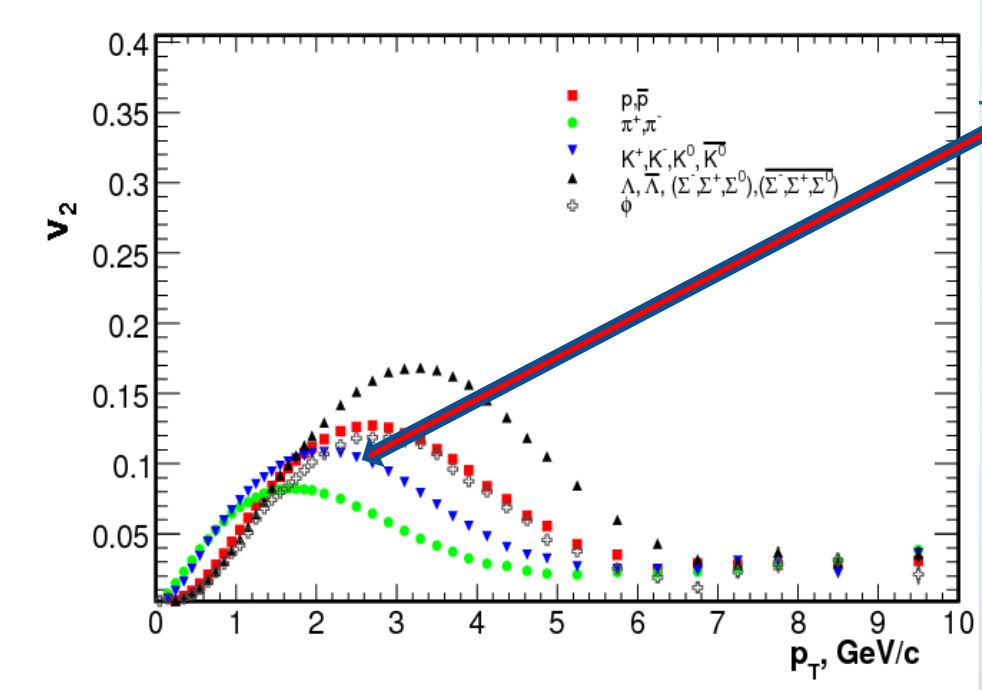
I.Lokhtin, L.Malinina, S.Petrushanko, A.Snigirev, I.Arsene, K.Tywoniuk,
Comp. Phys. Commun.180 (2009) 779-799 (arXiv:0809.2708[hep-ph])

• **The soft part** of HYDJET++ event represents the "thermal" hadronic state.
✓ multiplicities are determined assuming thermal equilibrium
✓ hadrons are produced on the hypersurface represented by a parameterization of relativistic hydrodynamics with given freeze-out conditions
✓ chemical and kinetic freeze-outs are separated
✓ decays of hadronic resonances are taken into account (360 particles from SHARE data table) with “home-made" decayer

the model reproduces soft hadroproduction features at RHIC (particle spectra, elliptic flow, HBT)

• **The hard**, multi-partonic part of HYDJET++ event is identical to the hard part of Fortran written HYDJET (PYTHIA6.4xx + PYQUEN1.5) => now PYTHIA Pro-Q20 tune !!
PYQUEN event generator is used for simulation of rescattering, radiative and collisional energy loss of hard partons in expanding quark-gluon plasma created in ultrarelativistic heavy ion AA collisions. HYDJET++ includes nuclear shadowing correction for parton distributions (important at LHC!)
Impact-parameter dependent parameterization of *nuclear shadowing (K.Tywoniuk, I.Arsene, L.Bravina, A.Kaidalov and E.Zabrodin, Phys. Lett. B 657 (2007) 170)*

V_2 in HYDJET++ for different particles (centrality 30%)

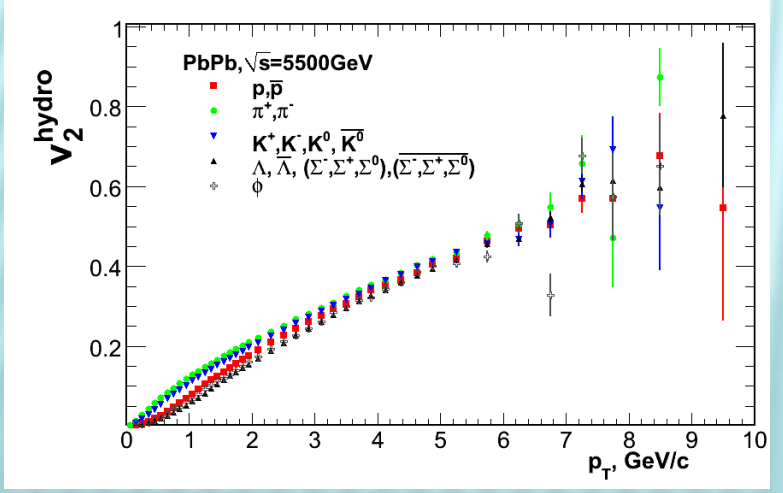


Mass ordering in soft p_T regions then breaks.

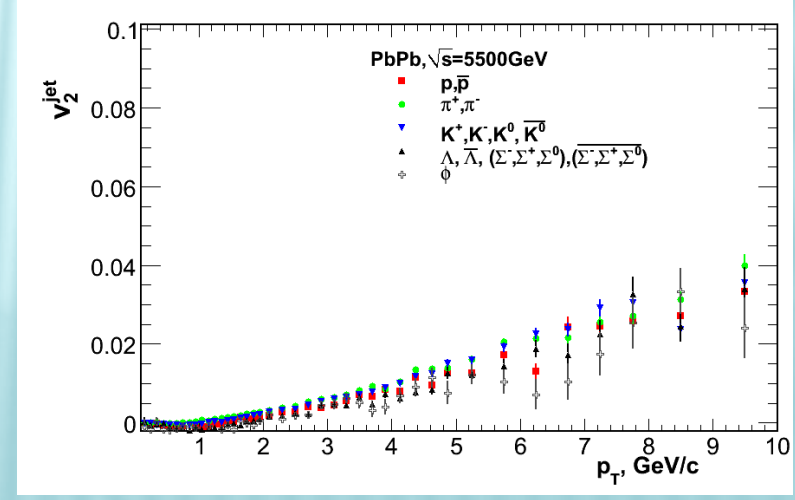
Why?

Hydrodynamics gives mass ordering of v2.
The model possesses crossing of baryon and meson branches.

Hydrodynamics



Jet part +quenching



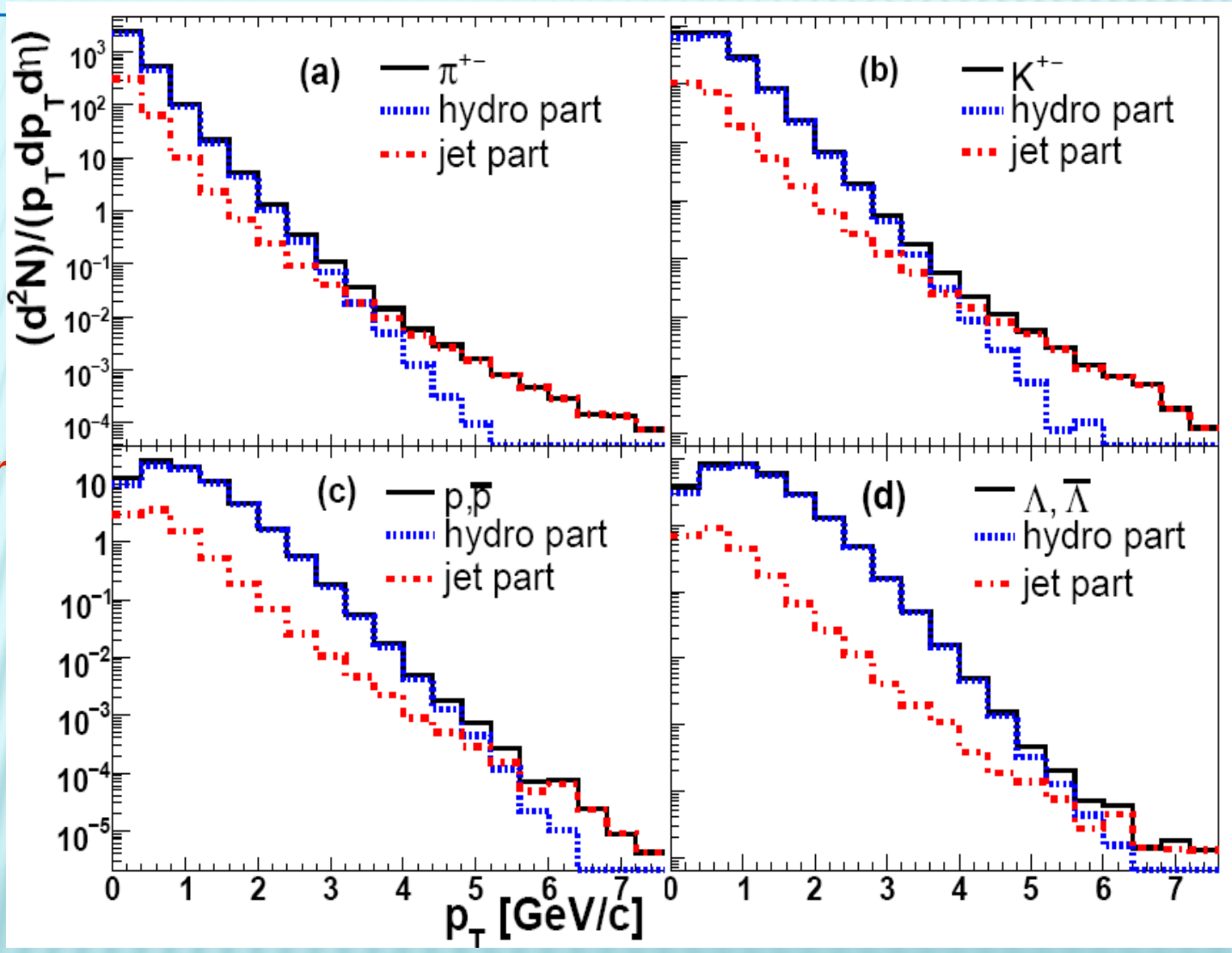
Interplay of hydrodynamics and jets

The p_T specta of π, K, p, Λ with HYDJET++ model, √s=200GeV

The slope for the hydro part depends strongly on mass:

- the heavier the particle -- the harder the spectrum

The hydro part dies out earlier for light particles than for heavy ones

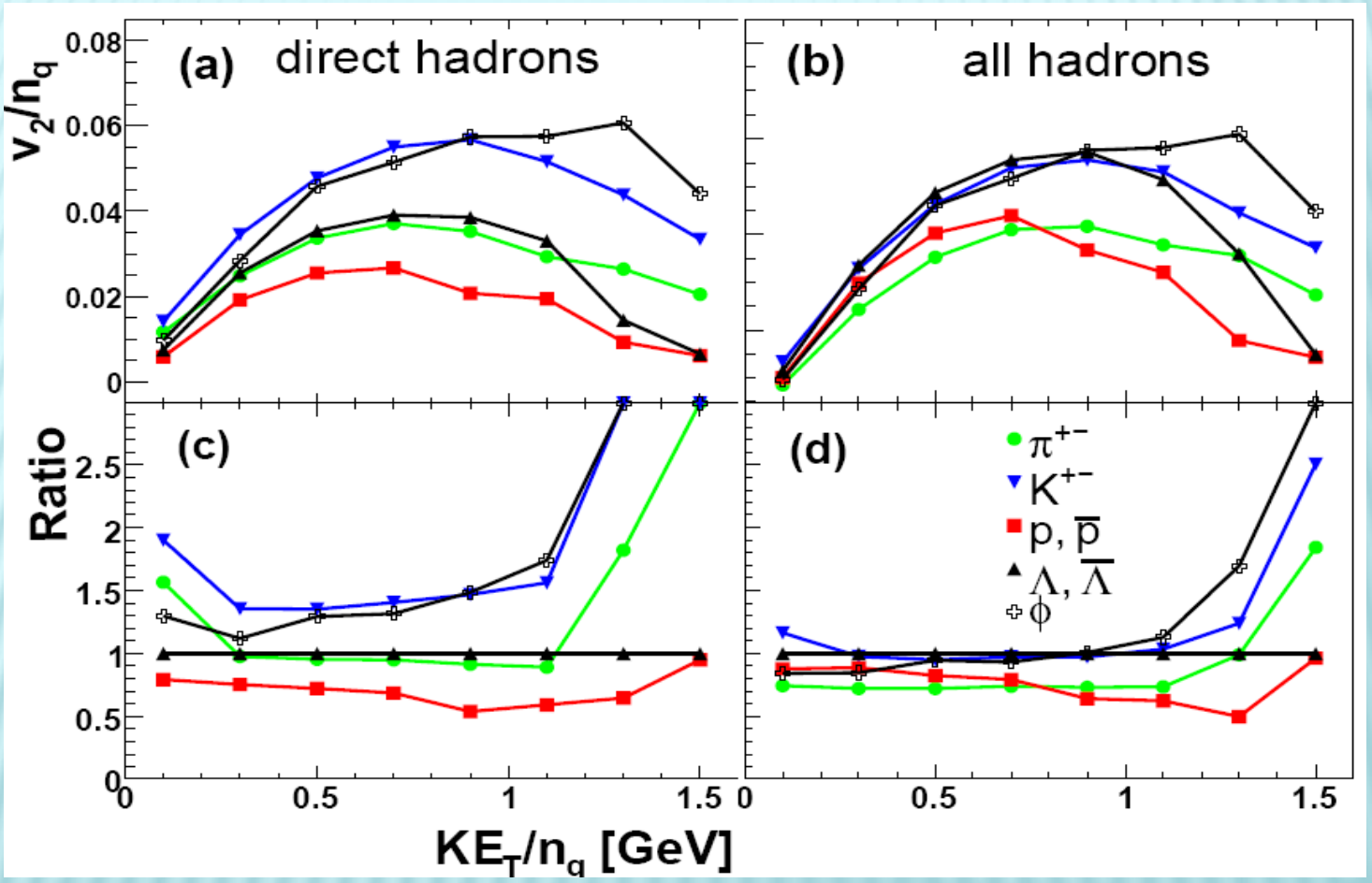


III. INFLUENCE OF JETS ON NCQ-SCALING AND V4/(V2*V2) RATIO

NCQ scaling at LHC

No scaling for direct particles

Appearance of the approximate scaling for all particles



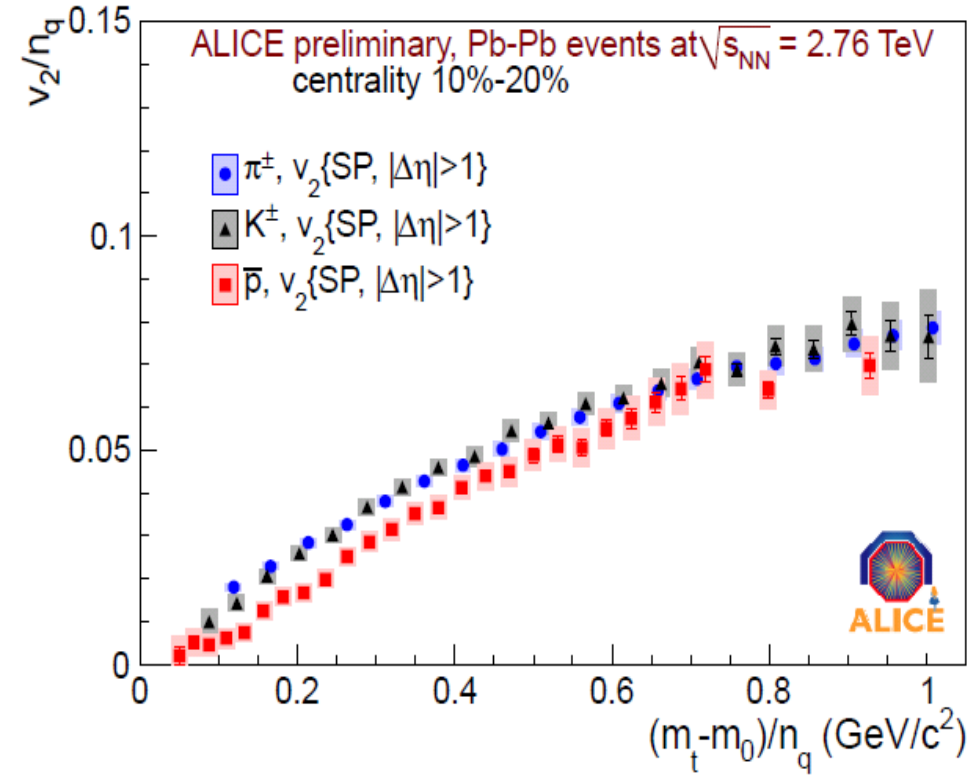
G.Eyyubova et al., PRC 80 (2009) 064907

LHC: NCQ scaling will be only approximate (prediction, 2009)

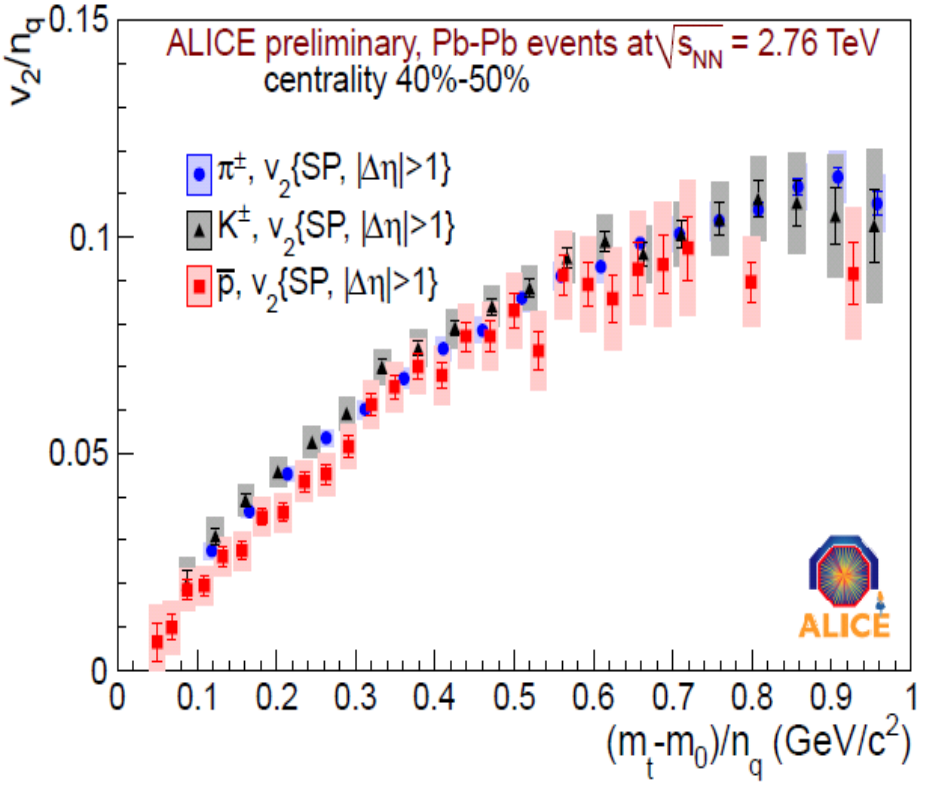
Experimental results (LHC)

ALICE Collaboration, M. Krzewicki et al., JPG 38 (2011) 124047

Semi-sentral collisions

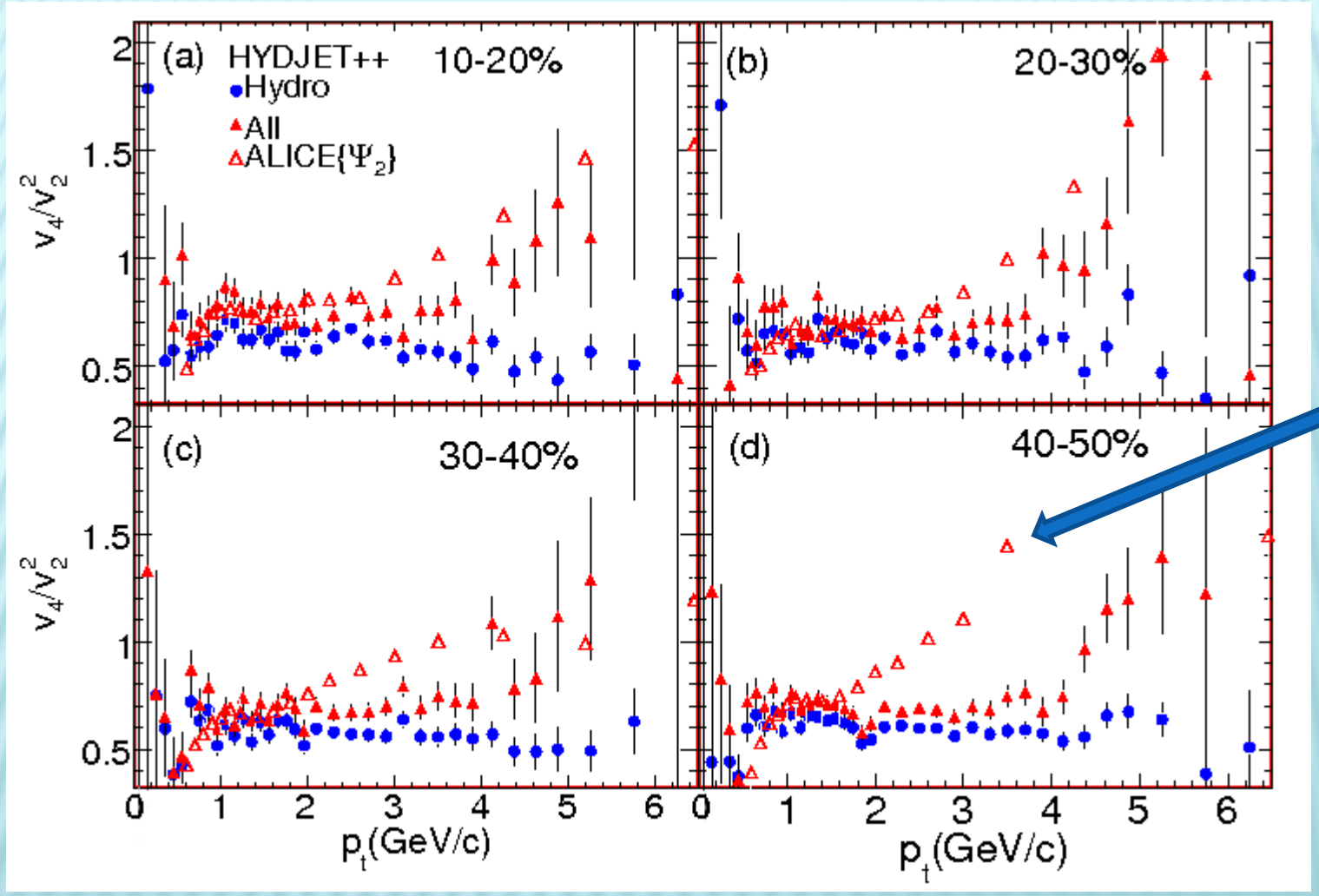


Semi-peripheral collisions



The NCQ scaling is indeed only approximate (2011)

HYDJET++ RESULTS FOR LHC



Jets increase the ratio and lead to rise of high-pT tail

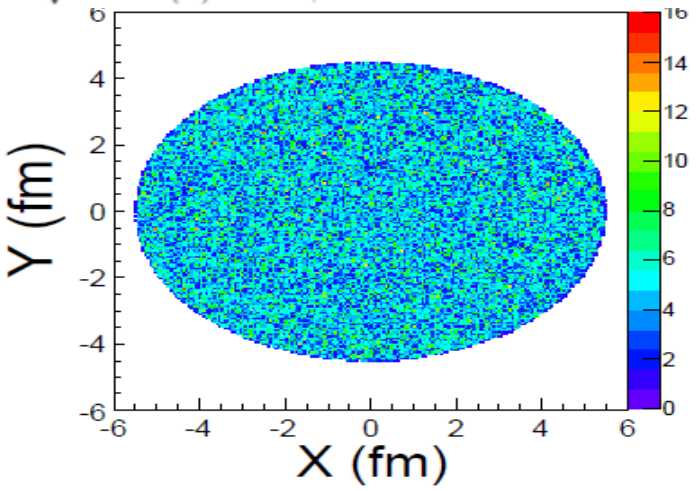
IV. Higher harmonics: hexagonal flow v6

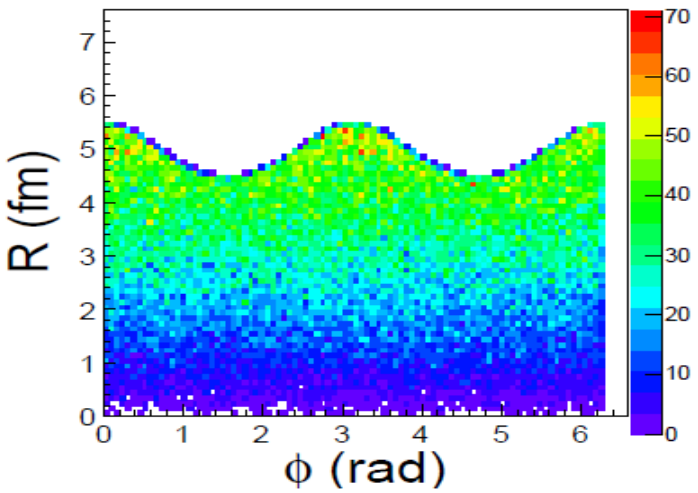
GENERATION OF TRIANGULAR FLOW

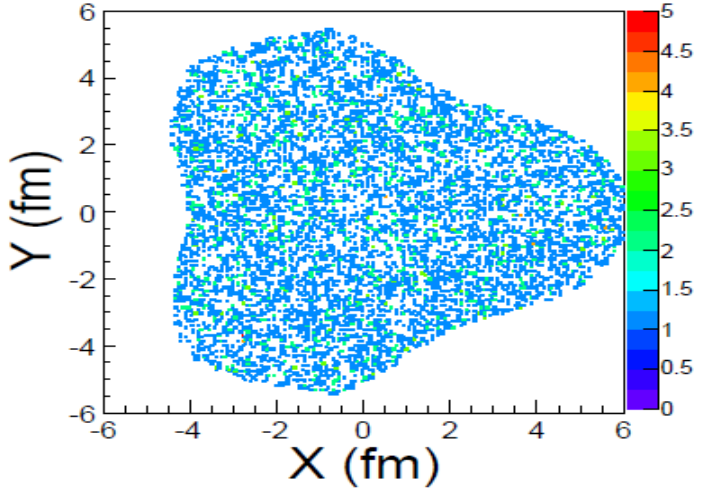
$$R(b,\phi) = R_f(b)\frac{\sqrt{1-\epsilon^2(b)}}{\sqrt{1+\epsilon(b)\cos 2\phi}}[1+\epsilon_3(b)\cos 3(\phi+\Psi_3^{\mathrm{RP}})]$$

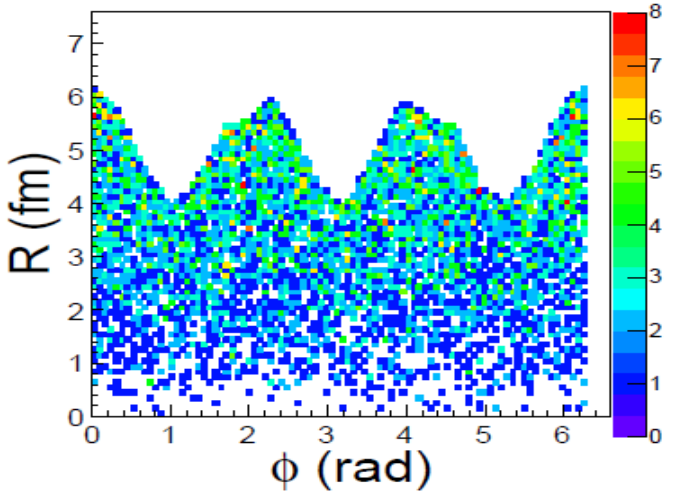
Bravina et al., EPJC 74:2807 (2014)

V2







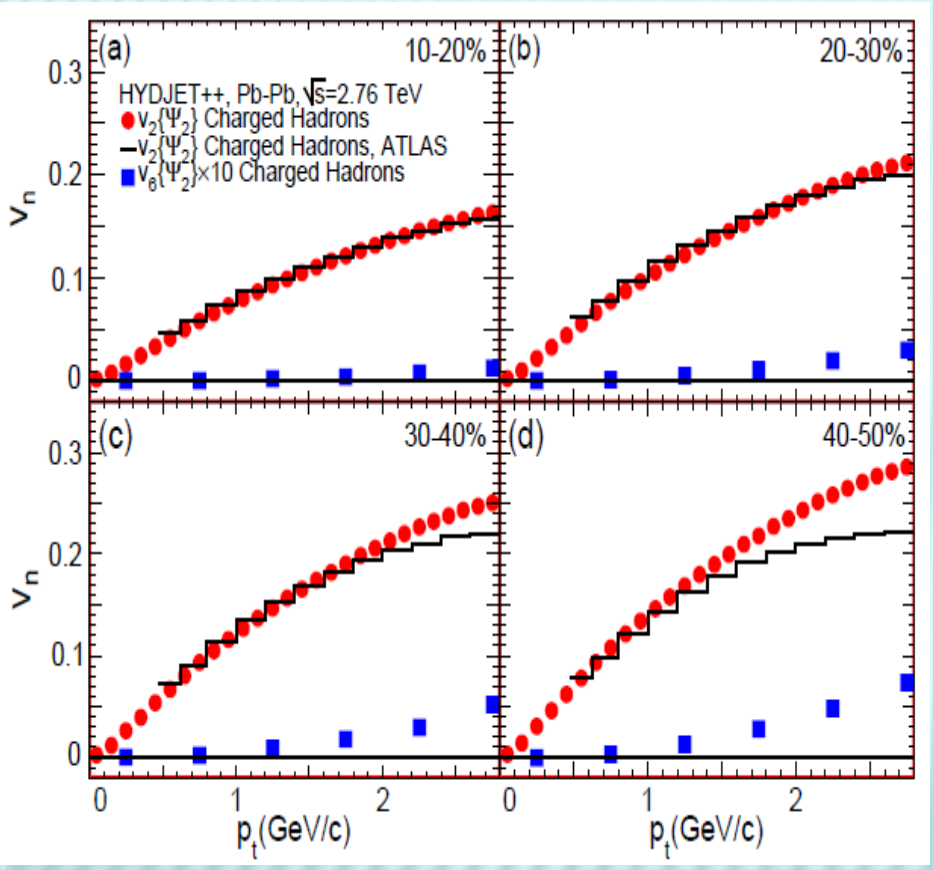


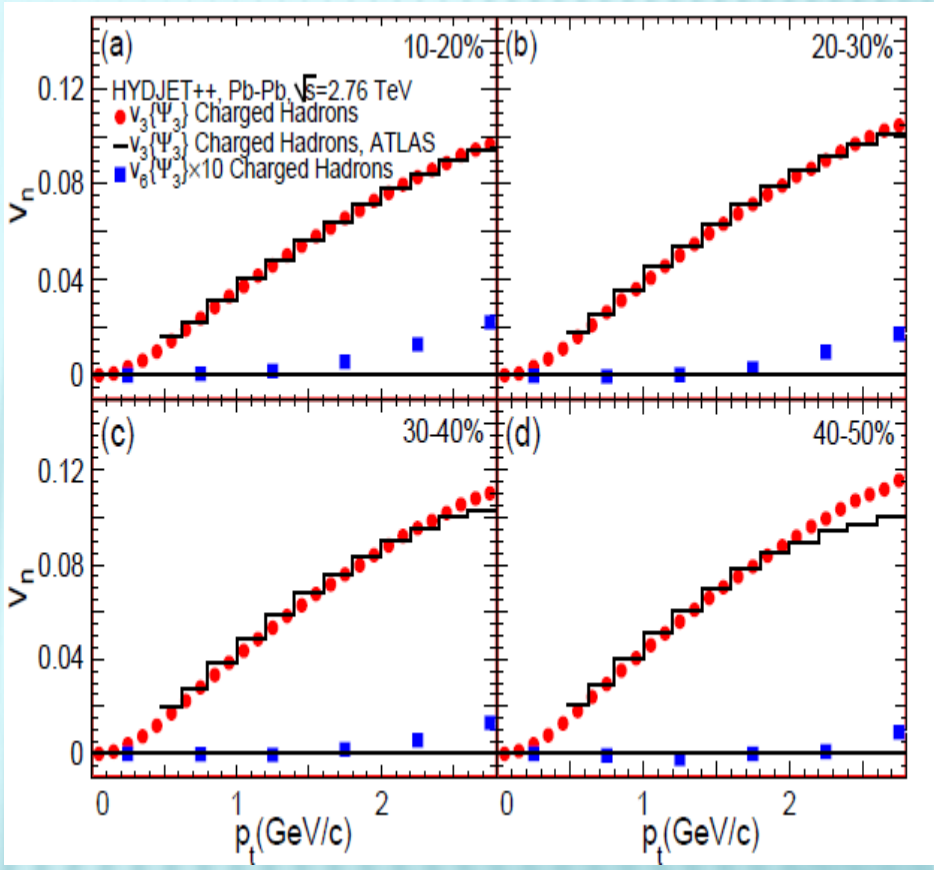
V3

Hint (Teaney, Ollitrault, …): $V_5 \propto V_2 V_3 \quad V_6 \propto \alpha V_2^3 + \beta V_3^2$

HEXAGONAL FLOW IN HYDJET++ AT LHC

Bravina et al., PRC 89, 024909 (2014)



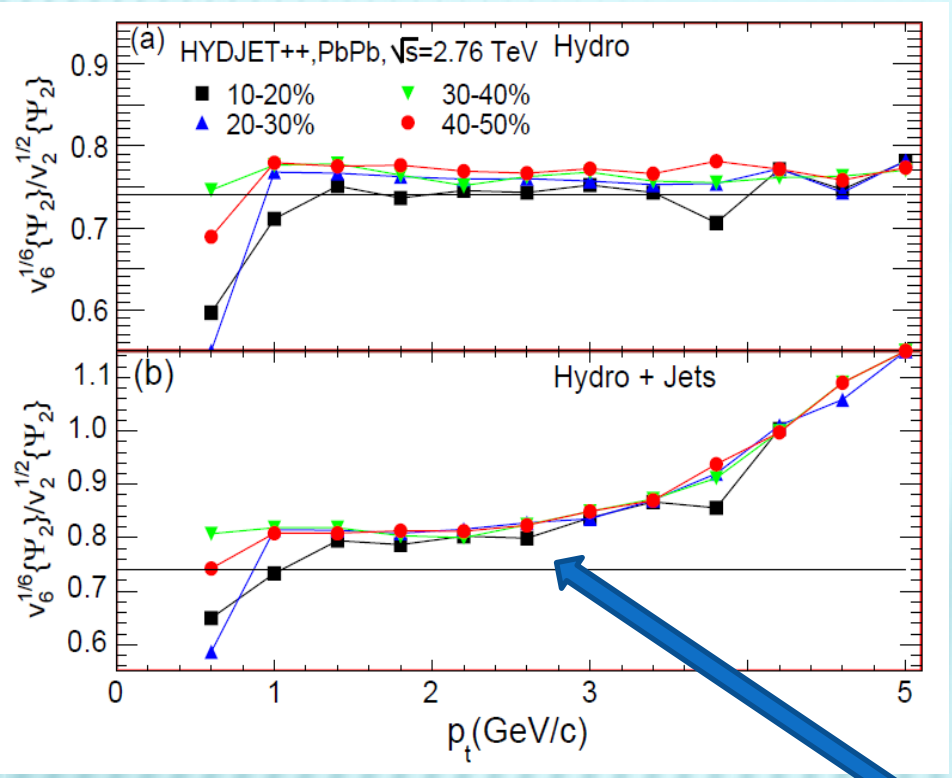


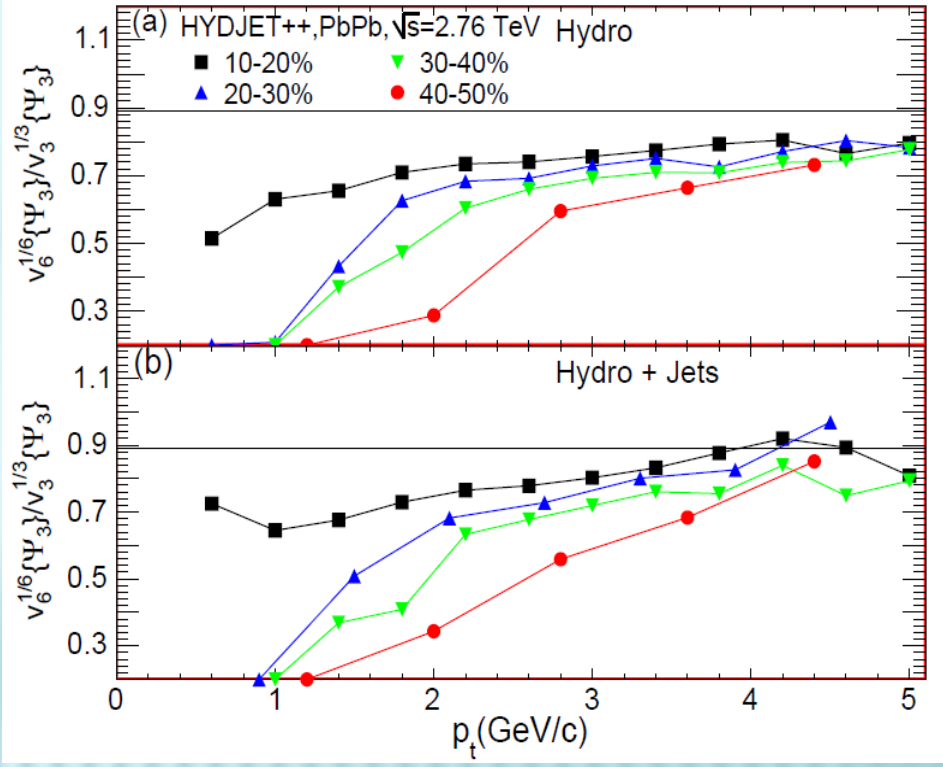
(1) V6 is weak

(2) Its high-pt tail increases with rising pT

Hexagonal flow: $V_6 \propto \alpha V_2^3 + \beta V_3^2$

Bravina et al., PRC 89, 024909 (2014)

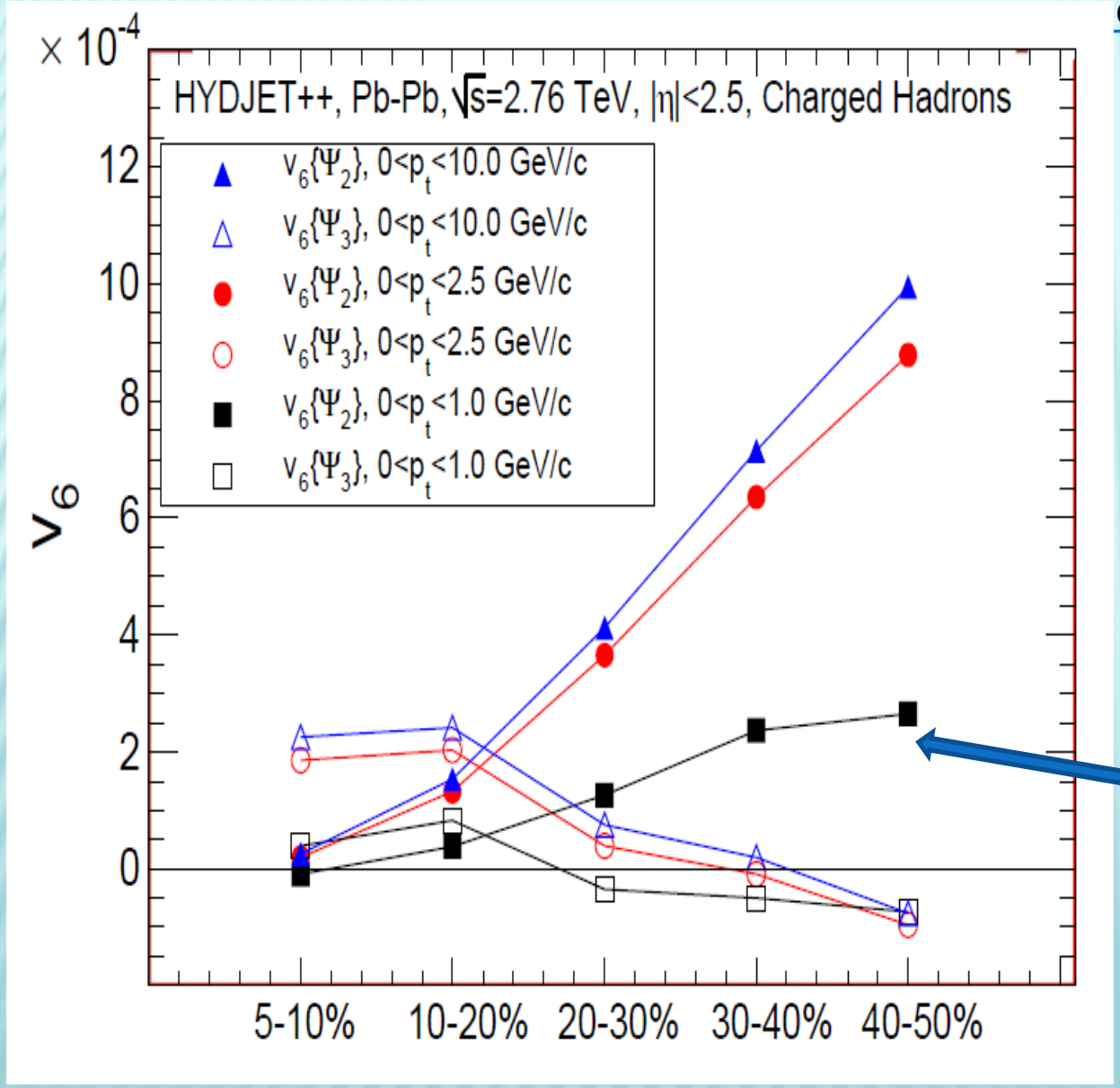




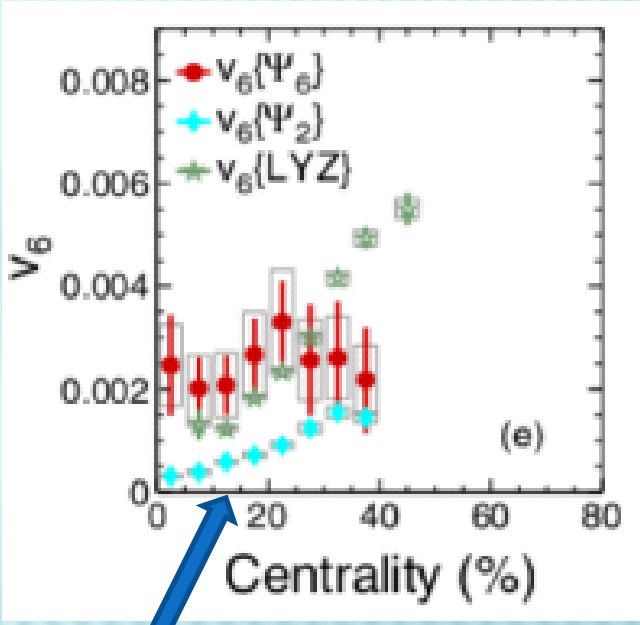
Ψ_2 Scaling? Ψ_3

It would be interesting to study $V_6(\Psi_2)$ **and** $V_6(\Psi_3)$ **in experiment**

Hexagonal flow: centrality dependence



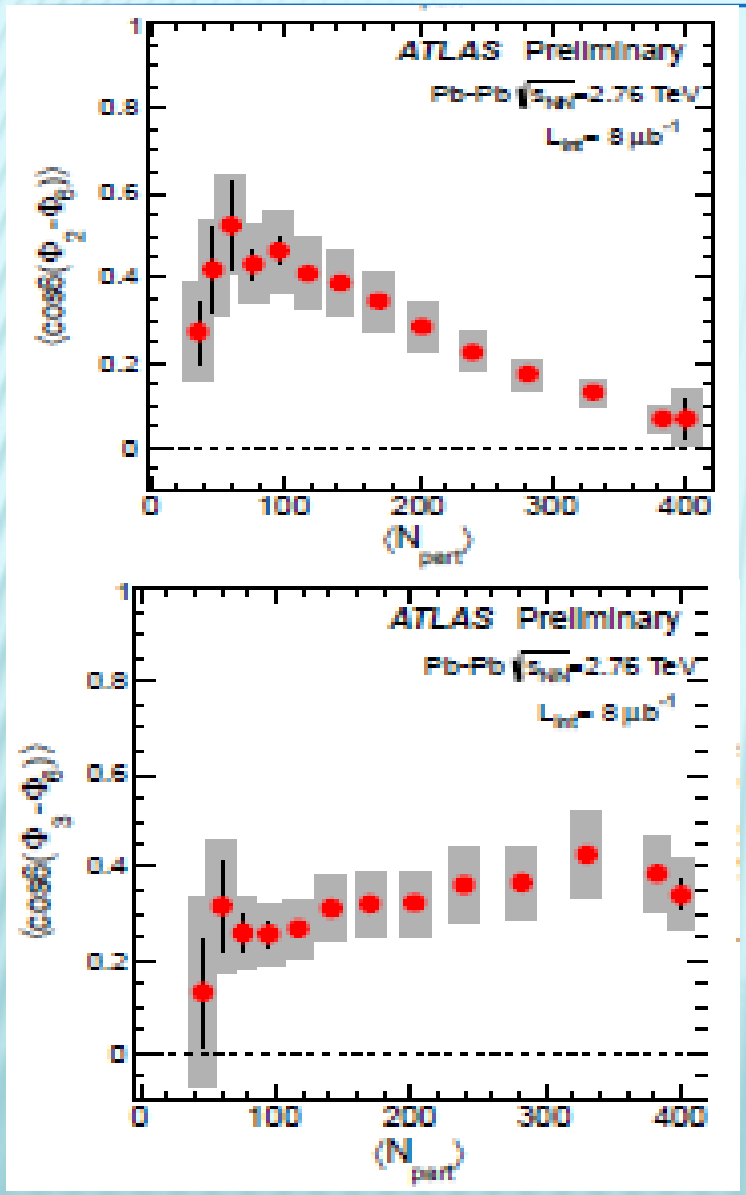
CMS Collab., PRC 89, 024909 (2014)

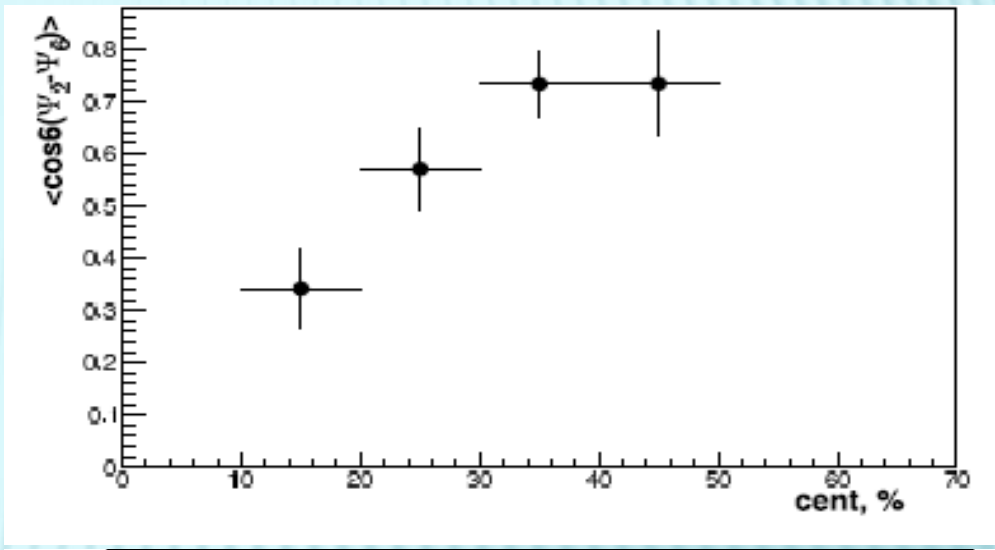


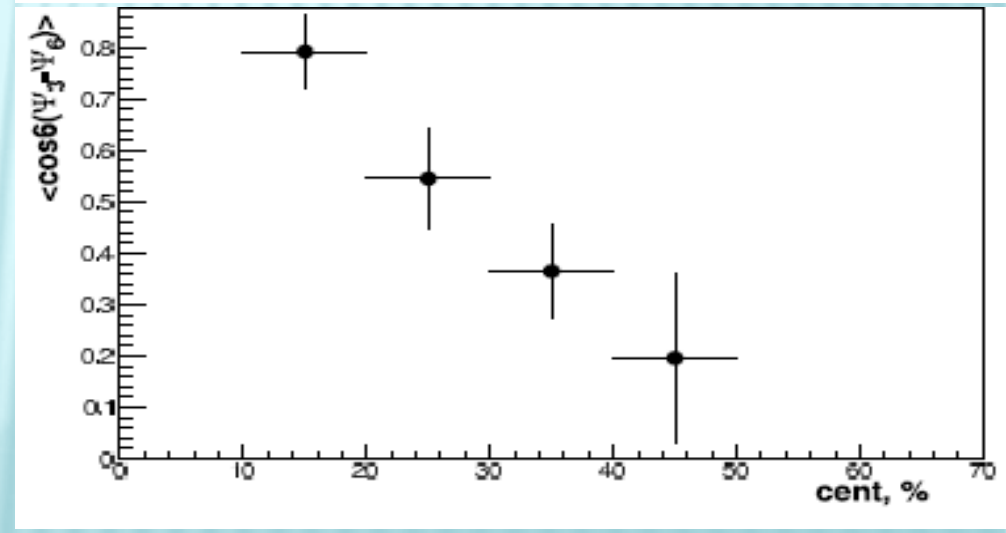
Centrality dependence in HYDJET++ is correct

Hexagonal flow: correlator analysis

ATLAS-CONF-2012-049







In line with experimental data

CONCLUSIONS

The HYDJET++ model allows us to investigate flow of hydro and jet parts separately, to look at reconstruction of pure hydro flow and its modification due to jet part.

- ***Jets + eccentricity fluctuations are enough to explain both RHIC and LHC data***
- ***Jets result to increase by 25%-30% of the ratio v4/(v2*v2) and lead to rise of the high-pT tail of the ratio***
- ***The predicted violation of the NCQ scaling at LHC is observed***
- ***Hexagonal flow and other higher order harmonics – just interplay of elliptic and triangular flows ?***

Back-up Slides

Model parameters.

1. Thermodynamic parameters at chemical freeze-out: **T_{ch}** , **$\{\mu_B, \mu_S, \mu_Q\}$**
2. If thermal freeze-out is considered: **T_{th}** , **μ_π**-normalisation constant
3. Volume parameters: **T, ΔT, R**
1. $\rho_u^{\max}$ -maximal transverse flow rapidity for Bjorken-like parametrization
5. **η_{max}** -maximal space-time longitudinal rapidity which determines the rapidity interval **$[-\eta_{max}, \eta_{max}]$** in the collision center-of-mass system.
6. Impact parameter range: minimal **b_{min}** and maximal **b_{max}** impact parameters
7. Flow anisotropy parameters **$\delta(b)$**, **$\varepsilon(b)$**

PYTHYA+PYQUEN obligatory parameters

9. Beam and target nuclear atomic weight **A**
10. $\sqrt{s_{NN}}$ –c.m.s. energy per nucleon pair (PYTHIA initialization at given energy)
11. **ptmin** – minimal pt of parton-parton scattering in PYTHIA event (ckin(3) in /pysubs/)
12. **nhsel** flag to include jet production in hydro-type event:

0 - jet production off (pure FASTMC event),
1 - jet production on, jet quenching off (FASTMC+njet*PYTHIA events),
2 - jet production & jet quenching on (FASTMC+njet*PYQUEN events),
3 - jet production on, jet quenching off, FASTMC off (njet*PYTHIA events),
4 - jet production & jet quenching on, FASTMC off (njet*PYQUEN events);

13. **ishad** flag to switch on/off nuclear shadowing

Parameters of energy loss model in PYQUEN

(default, but can be changed from the default values by the user)

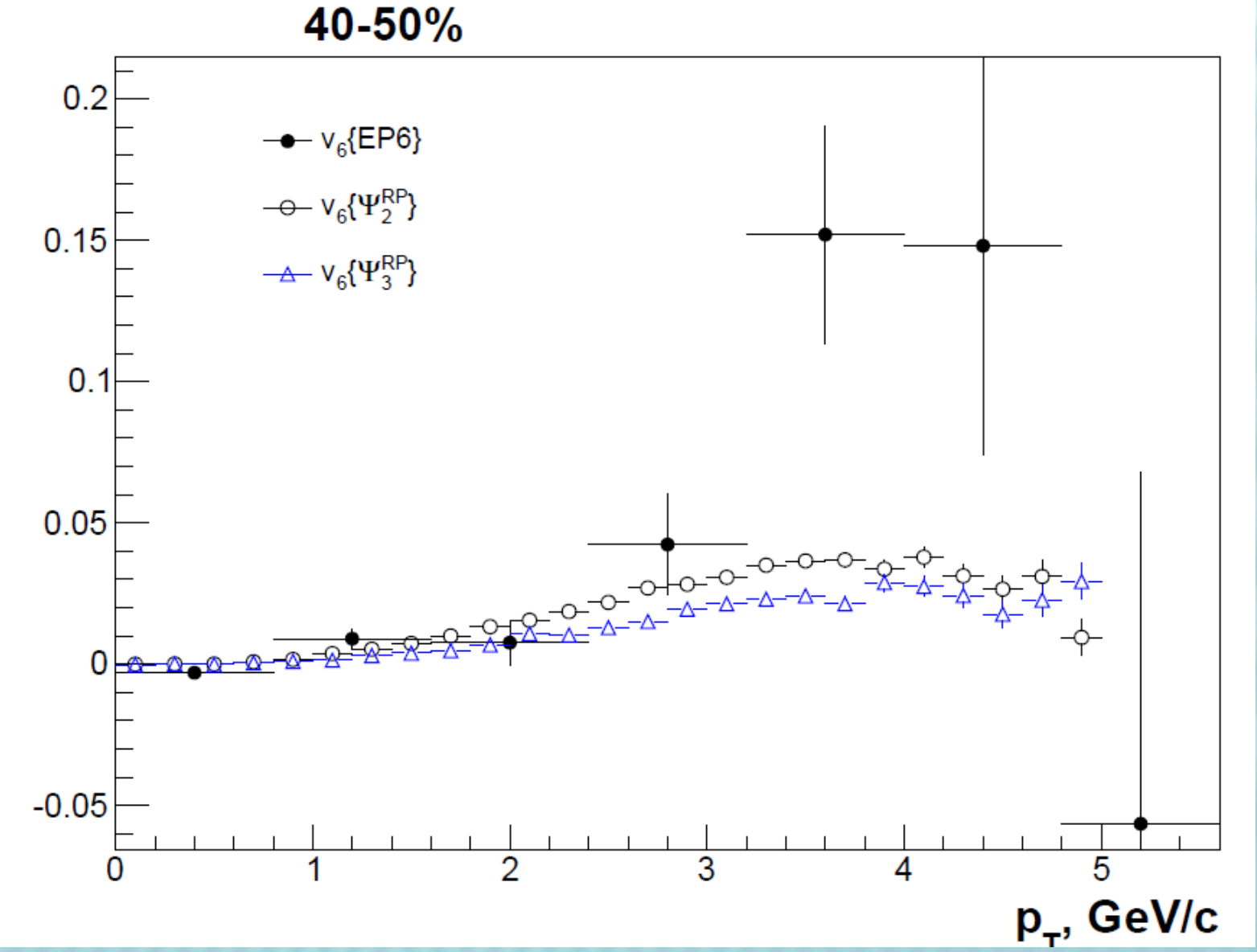
1. T0 - initial temparature of quark-gluon plasma for central Pb+Pb collisions at mid-rapidity (initial temperature for other centralities and atomic numbers will be calculated automatically) at LHC: T0=1 GeV, at RHIC(200 AGeV) T0=0.300 GeV

2. tau0 - proper time of quark-gluon plasma formation at LHC: tau0=0.1 fm/c, at RHIC(200 AGeV) tau0=0.4 fm/c

3. nf - number of active quark flavours in quark-gluon plasma (nf=0, 1, 2 or 3) at LHC: nf=0, at RHIC(200 AGeV) nf=2

4. ienglu - flag to fix type of medium-induced partonic energy loss (ienglu=0 - radiative and collisional loss, ienglu=1 - radiative loss only, ienglu=2 - collisional loss only, default value is ienglu=0);
ianglu - flag to fix type of angular distribution of emitted gluons (ianglu=0 - small-angular, ianglu=1 - wide-angular, ianglu=2 - collinear, default value is ianglu-0).
ienglu=0

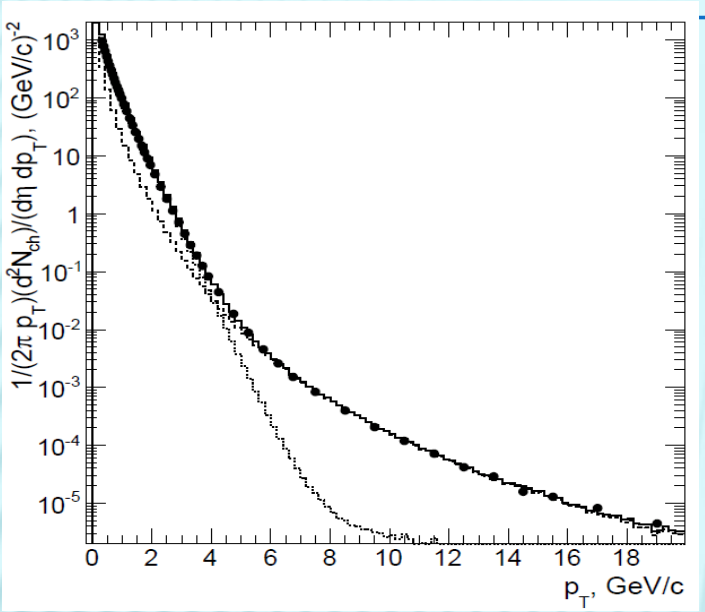
Extraction of V6 (Event Plane method)



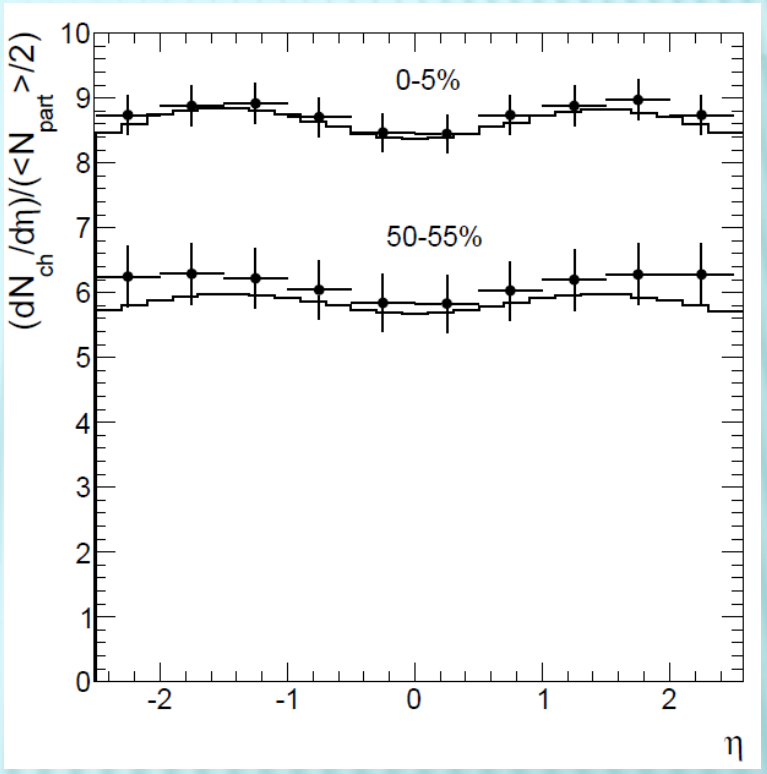
LHC DATA VS. HYDJET++ MODEL

Transverse momentum

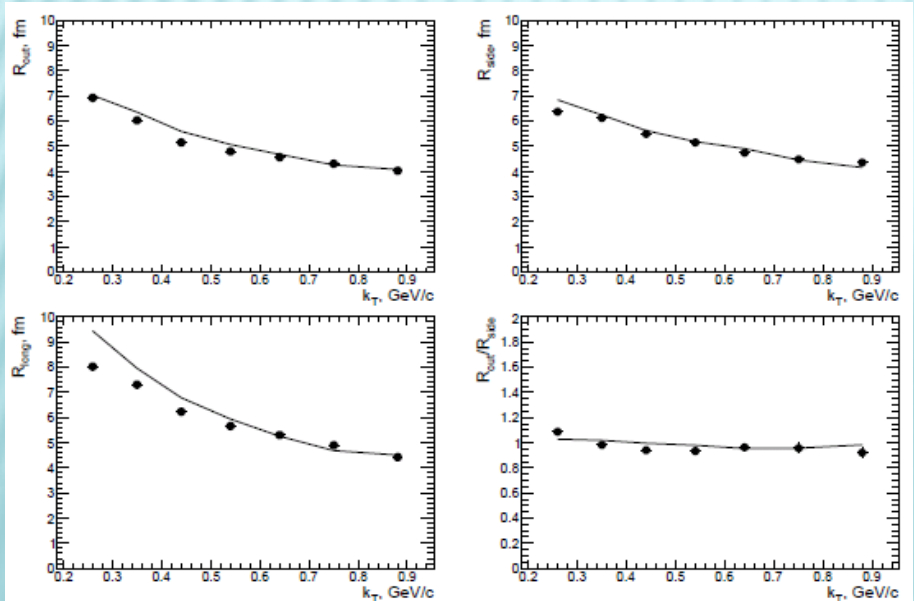
Pb+Pb @ 2.76 ATeV



Rapidity



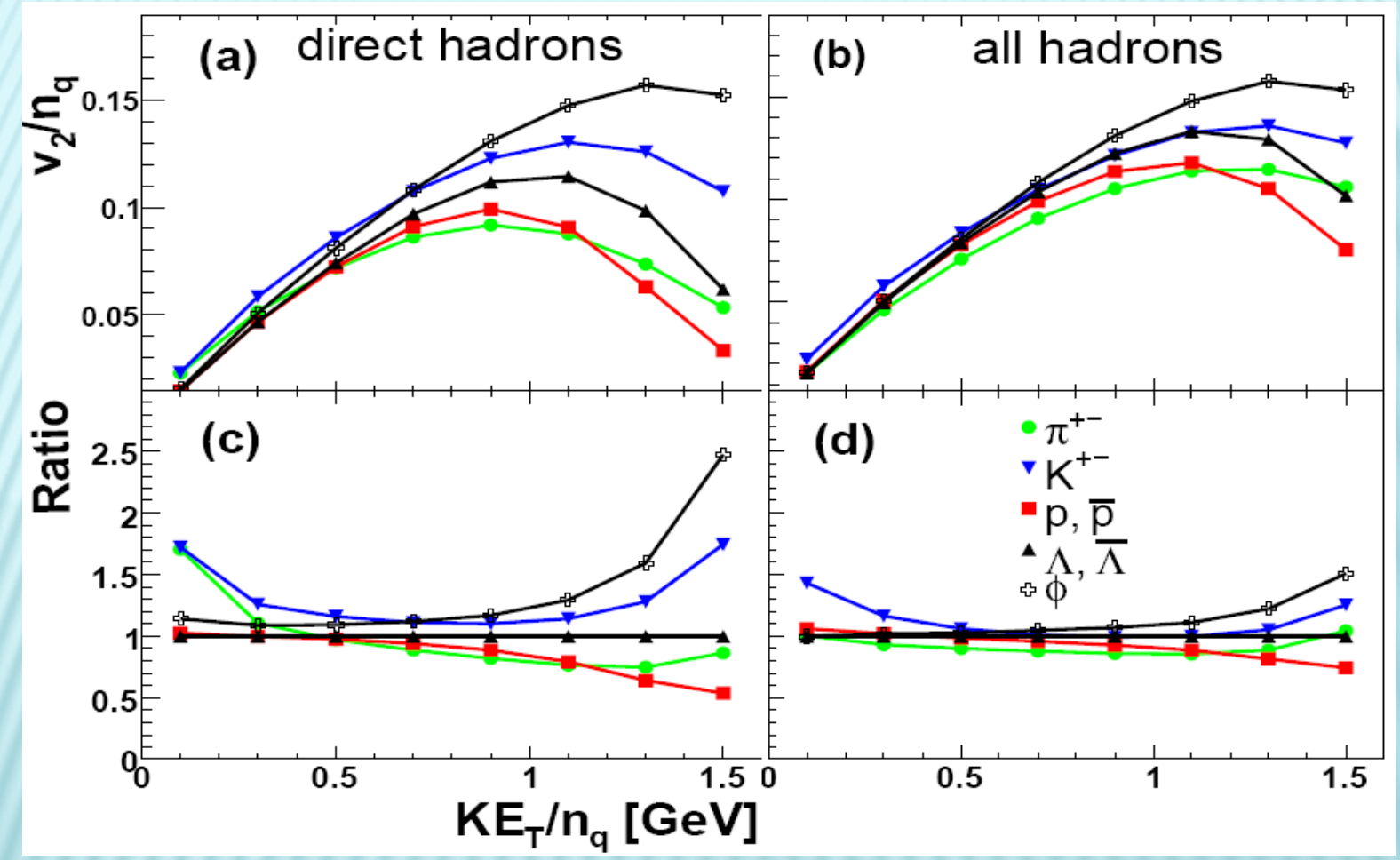
I. Lokhtin et al., Eur. Phys. J C72 (2012) 2045



Correlation radii (femtoscopy)

Number-of-constituent-quark scaling at RHIC

Direct particles: scaling is not good. All particles: KE_T/n_q scaling



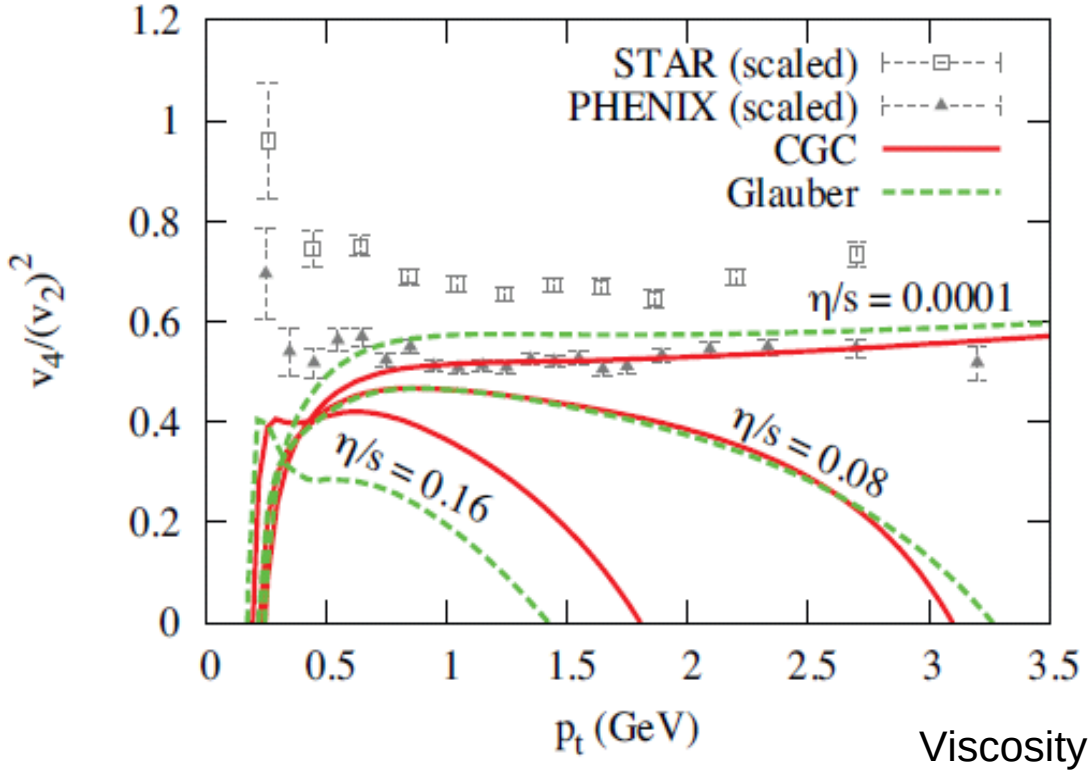
G.Eyyubova et al., PRC 80 (2009) 064907

One of the explanations of KE_T/n_q scaling is partonic origin of the elliptic flow.

However, final state effects (such as resonance decays and jets) may also lead to appearance of the scaling

M. Luzum, C. Gombeaud, J.-Y. Ollitrault, PRC 81 (2010) 054910

Effects of initial profile and viscosity



Initial profile has little effect although eccentricities differ.

results strongly depend on viscosity

Viscosity lowers v4 /(v2)^2 for a realistic T_f

Why ε fluctuations change v_4/v_2^2

Experimentally, no direct measure of v_2 and v_4

v_2 and v_4 are measured via azimuthal correlations

v_2 from $\langle cos(2\phi_1 - 2\phi_2)\rangle = \langle (v_2)^2\rangle$

v_4 from $\langle cos(4\phi_1 - 2\phi_2 - 2\phi_3)\rangle = \langle v_4(v_2)^2\rangle$

Experimentally measured

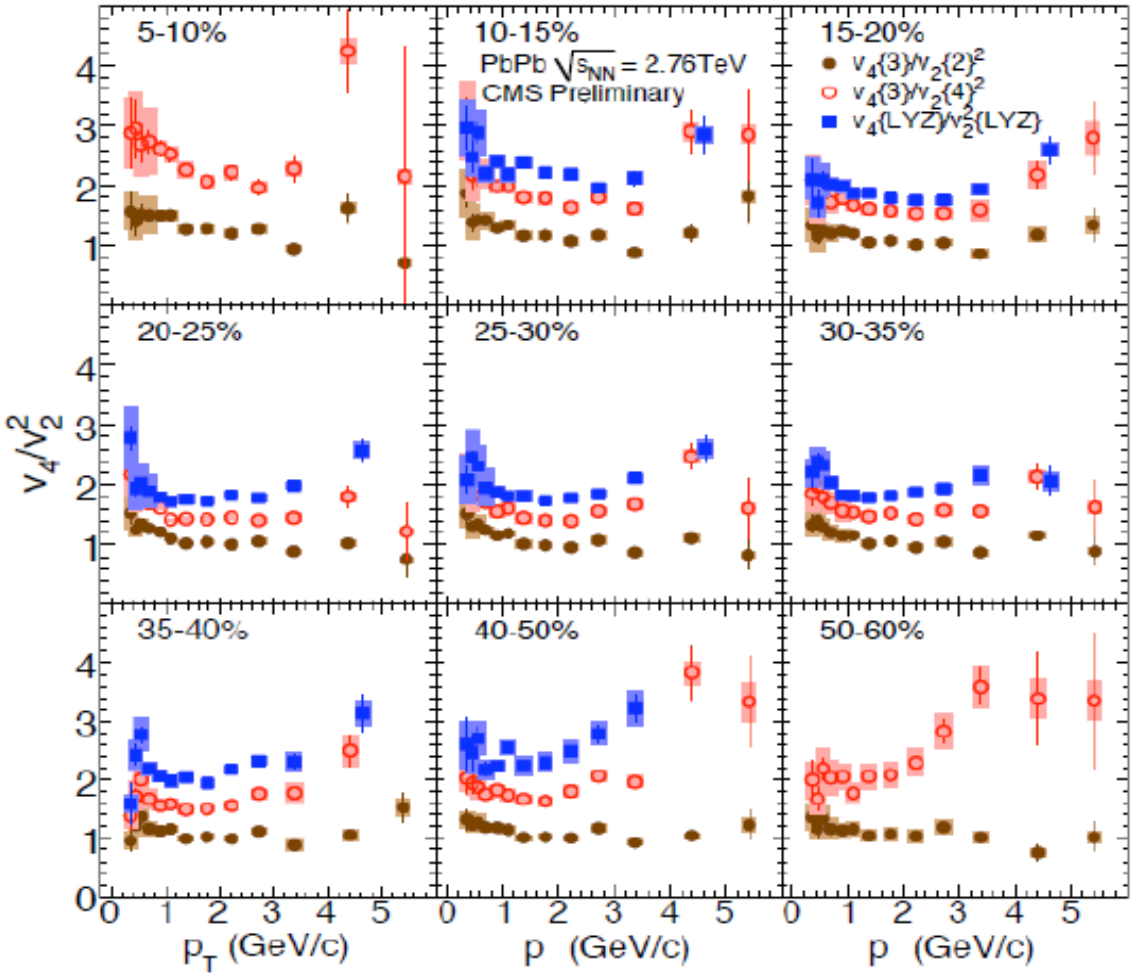
$$\frac{v_4}{v_2^2} = \frac{\langle v_4(v_2)^2\rangle}{\langle (v_2)^2\rangle^2} = \frac{1}{2}\frac{\langle (v_2)^4\rangle}{\langle (v_2)^2\rangle^2} > \frac{1}{2}$$

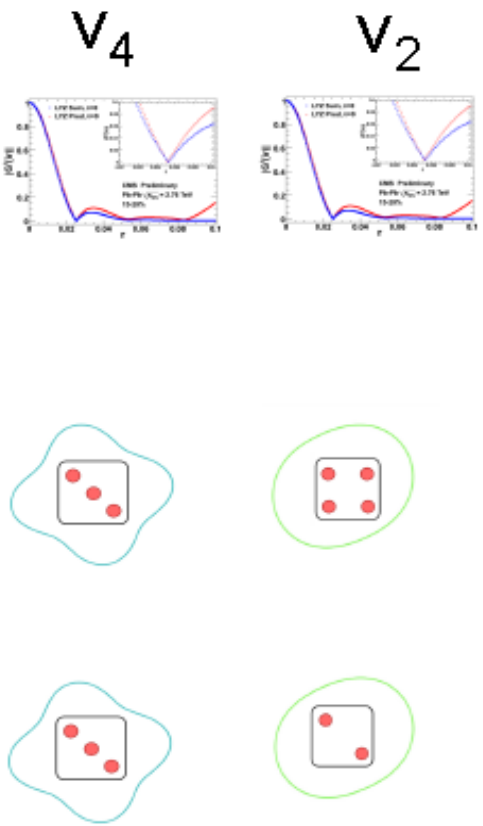
fluctuations

hydro

Similar results obtained using Event Plane method

$v_4 / v_2^2(p_T)$ at mid-rapidity $|\eta| < 0.8$

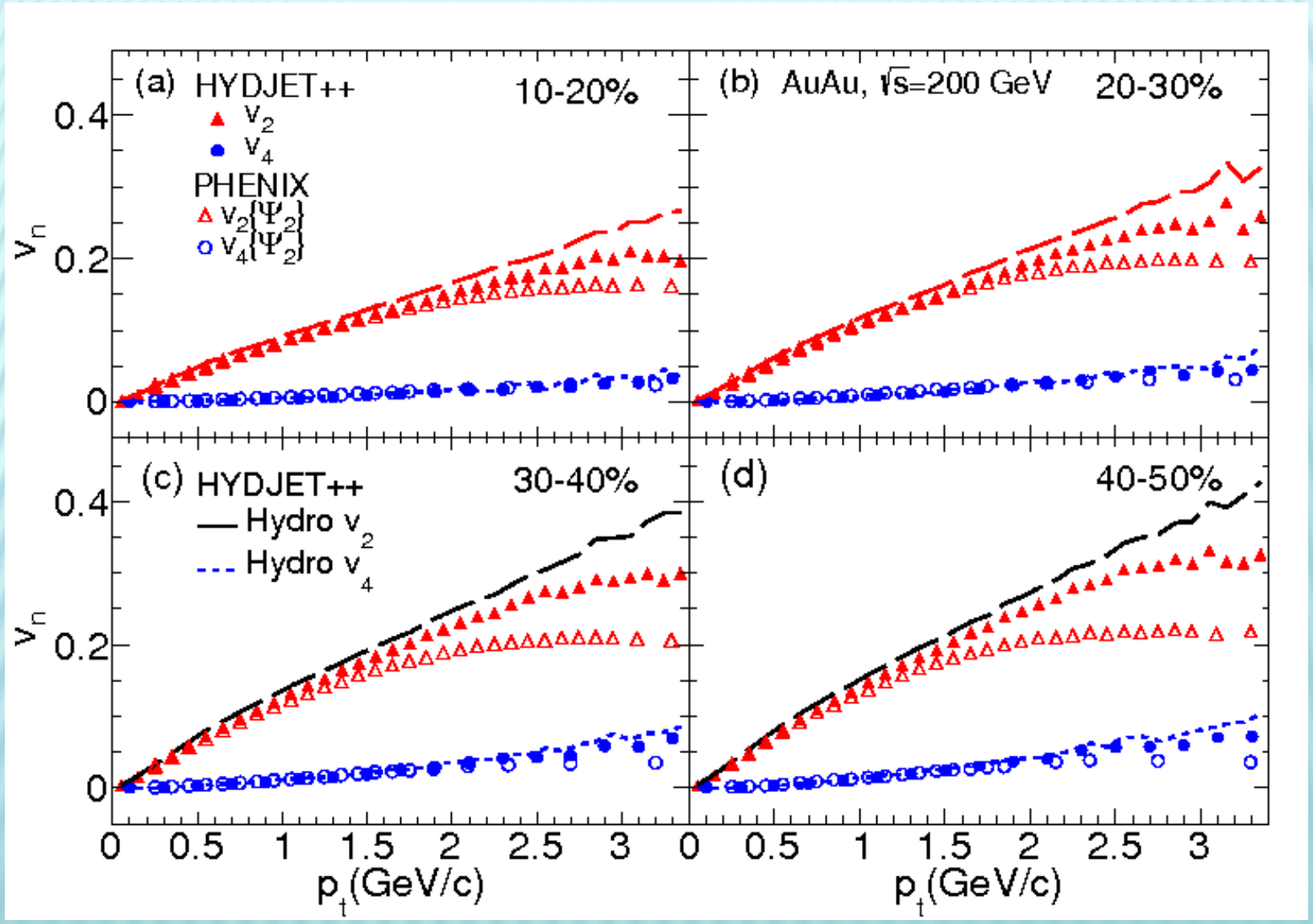




Significantly higher than RHIC: experimental method dependent

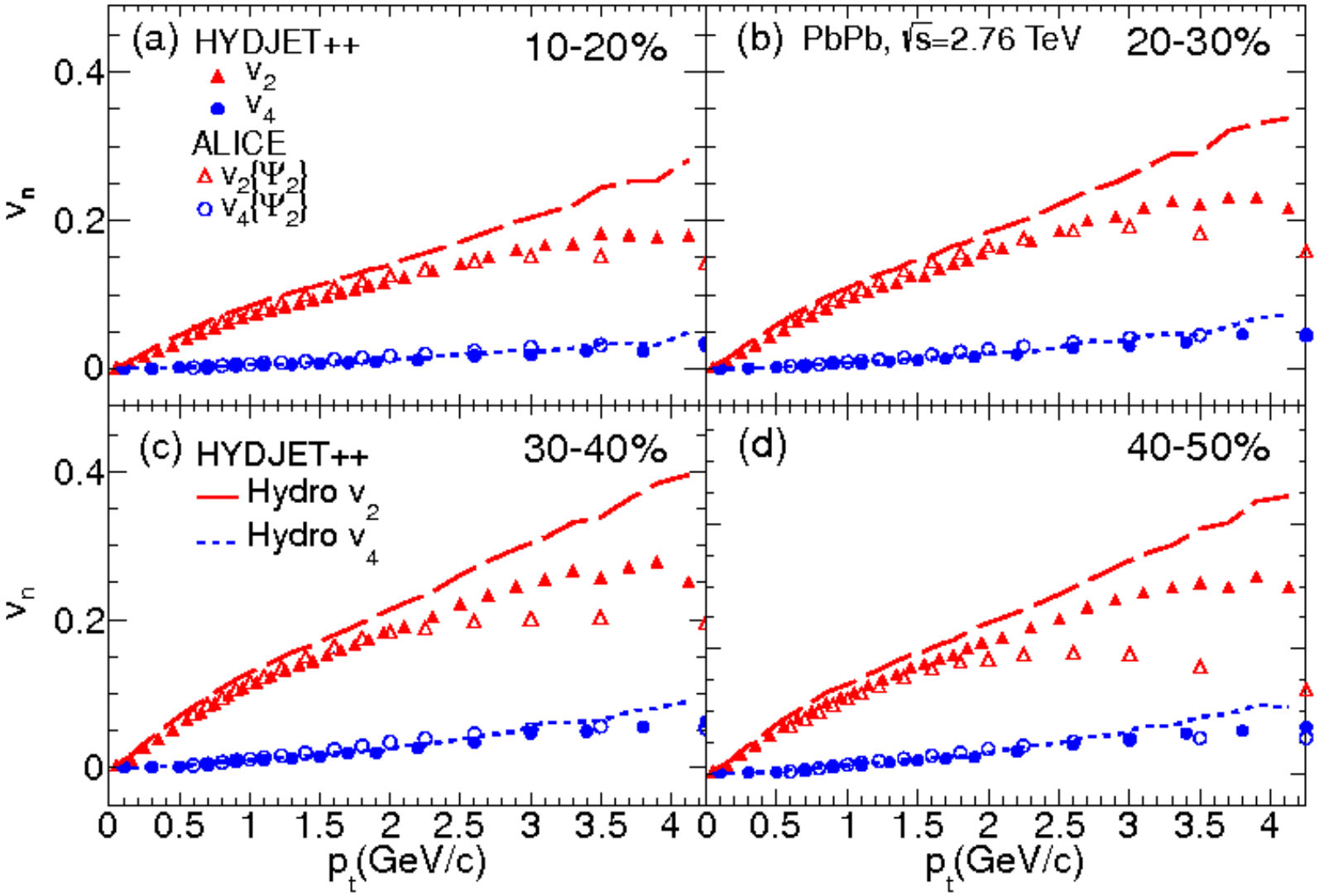
HYDJET++ (RHIC)

Effects to be studied: resonance decay and hard part influence



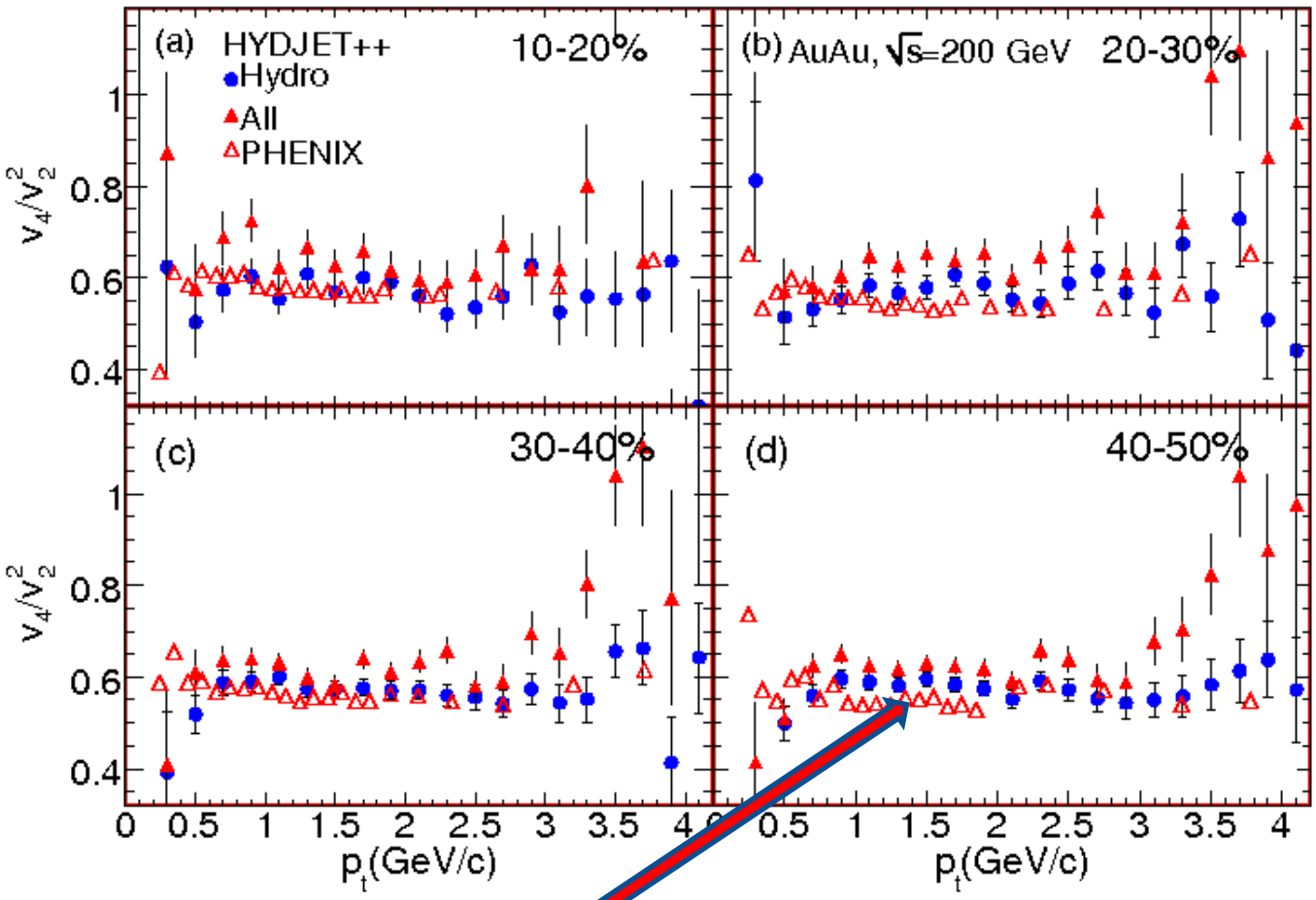
HYDJET++ (LHC)

Pure hydrodynamics vs hydro+jets



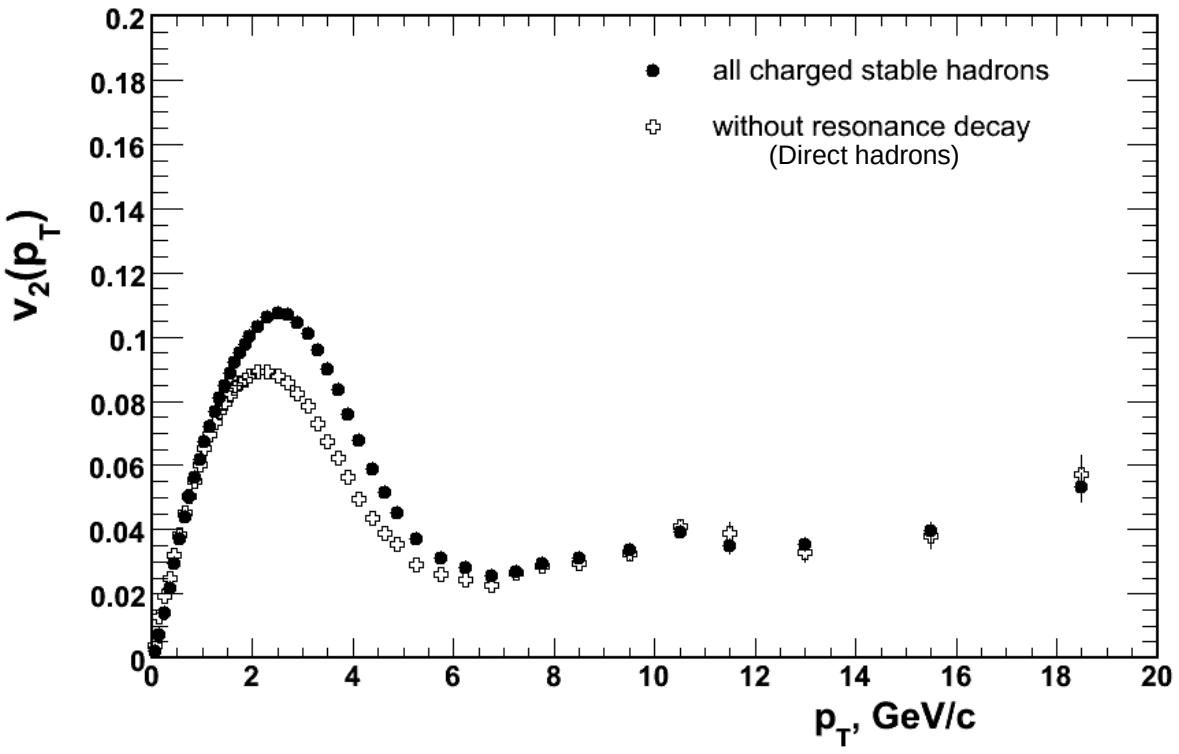
L.B. et al., PRC 80 (2013) 064907

HYDJET++ RESULTS FOR RHIC



Jets increase the ratio

Influence of resonance decay on v2 value



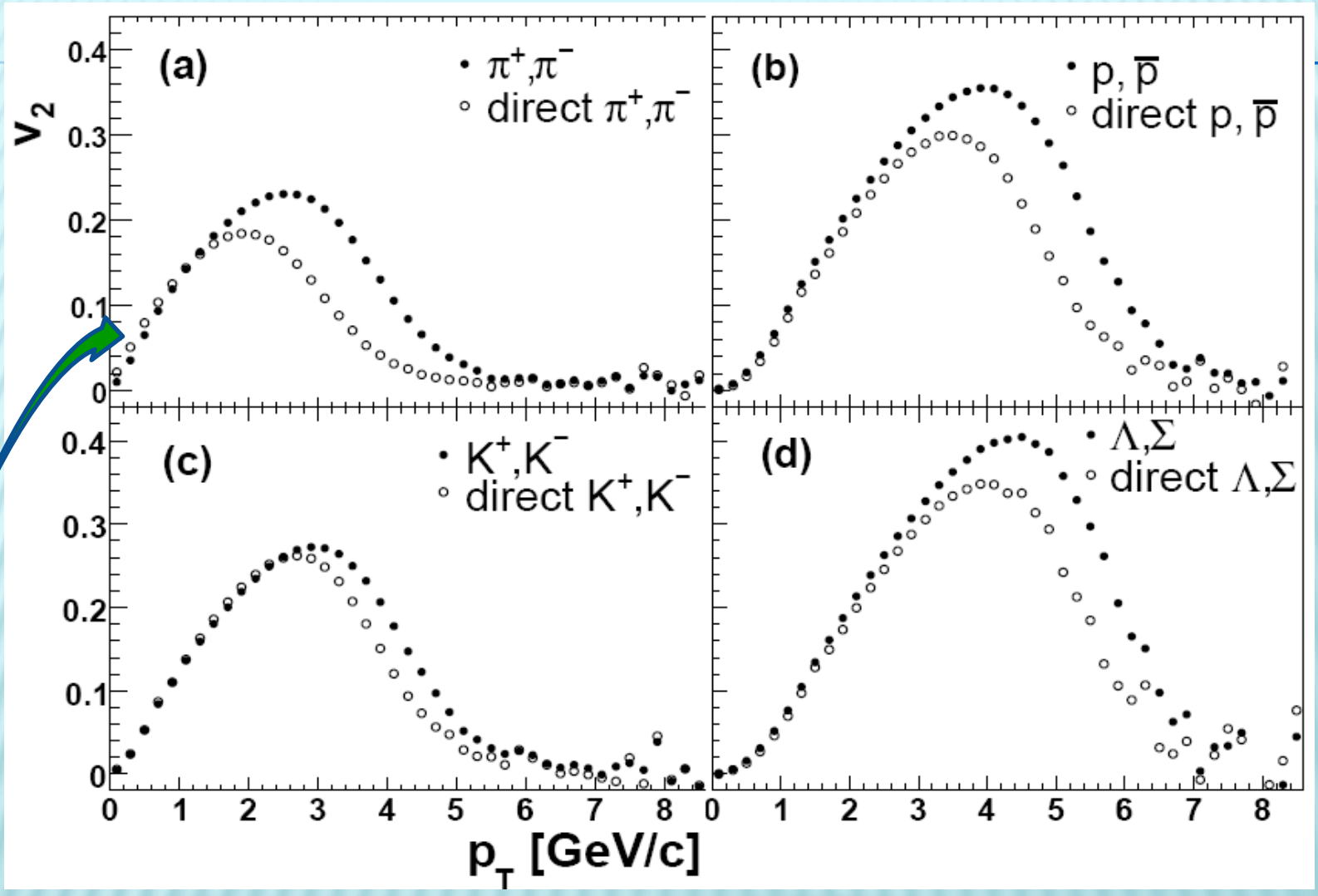
PbPb collisions, c=30%

The elliptic flow of directly produced particles is smaller than that for all particles.

TABLE I: Yelds of the particles produced directly and with resonance decays, $5.6 \cdot 10^6$ events, c=42%, midrapidity

	$\pi^{\pm}$	$K + \bar{K}$	$p + \bar{p}$	$\Lambda + \bar{\Lambda} + \Sigma + \bar{\Sigma}$	ϕ
all	860	185	63.8	42.3	6.55
direct	169	81.4	18.6	14.2	6.5
direct %	20 %	44 %	30 %	39 %	99 %

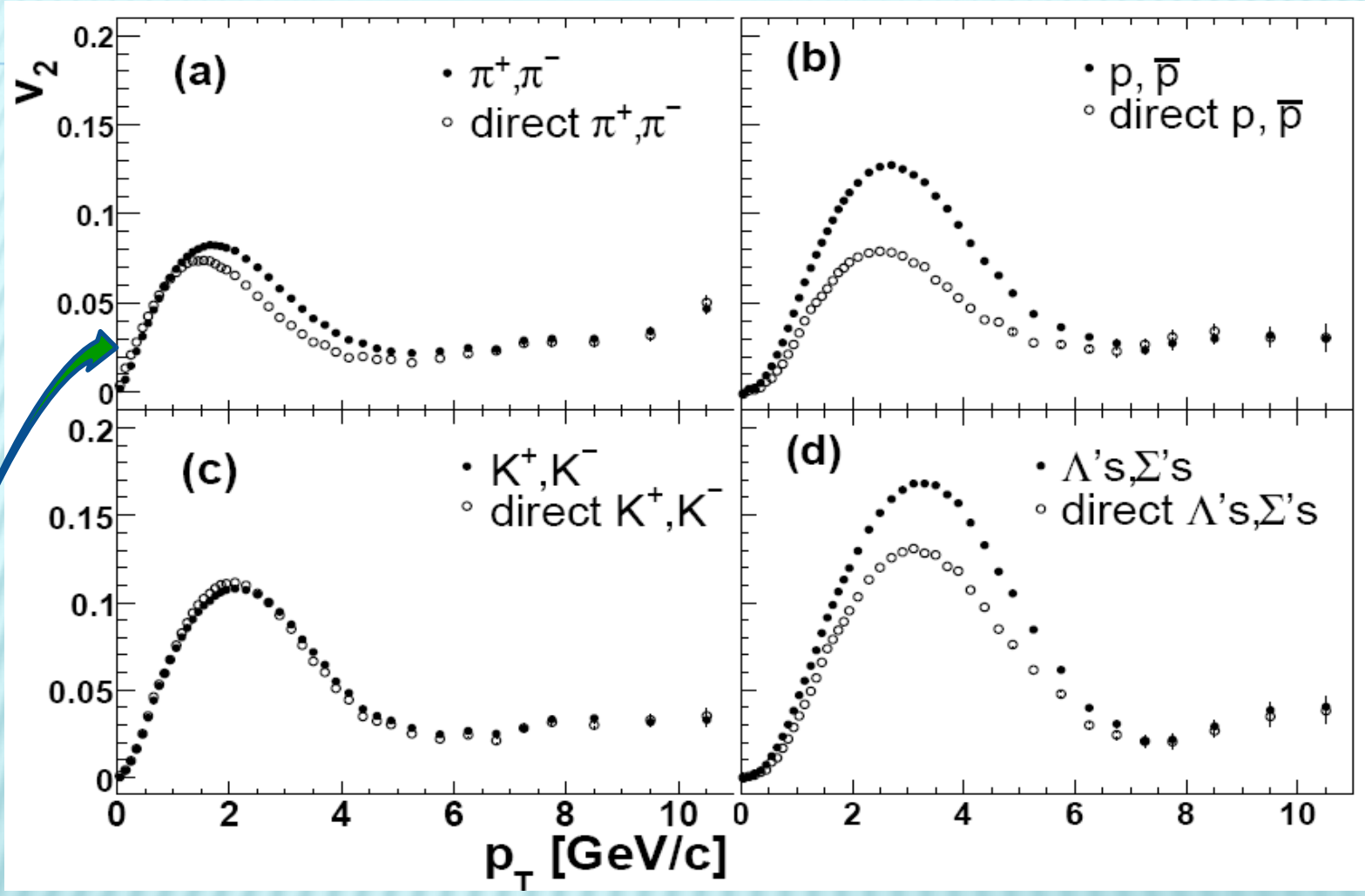
Influence of resonance decays for different type of particles at RHIC



Pions and kaons: the resulting flow is weaker at low-pt and larger at high-pt

Baryons: the resulting flow is stronger than the flow of direct particles

Influence of resonance decays for different type of particles at LHC



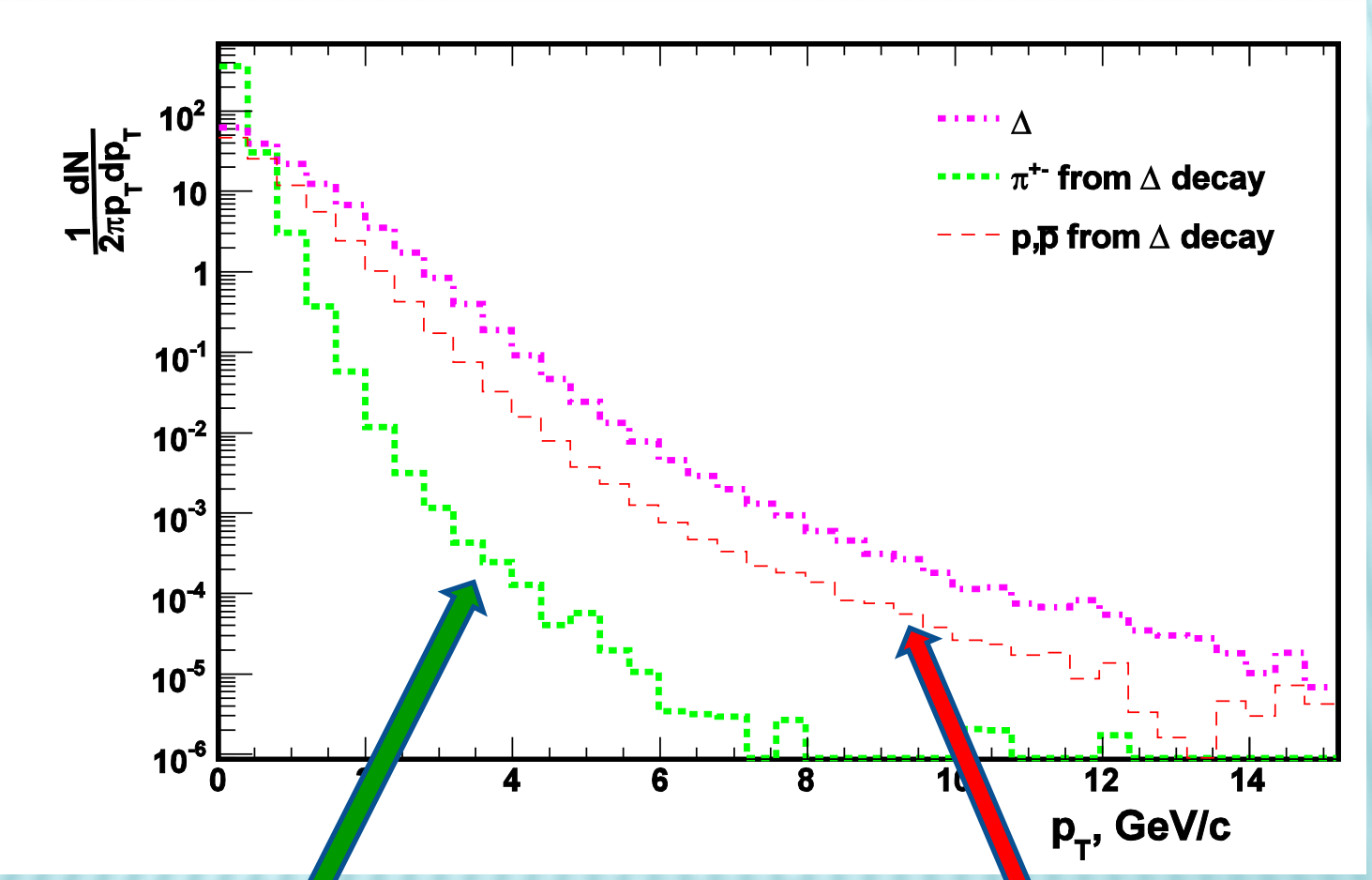
Pions: the resulting flow is weaker at low-pt and larger at high-pt

Kaons: both flows almost coincide

Baryons: the resulting flow is stronger than the flow of direct particles

TRANSVERSE MOMENTUM OF SECONDARY PARTICLES

$\Delta \rightarrow \pi + p$



The secondary pion spectrum is much softer than proton spectrum

Methods for v_2 calculation

(1) Event plane method

$$v_2^{obs}\{EP\} = \langle \cos 2(\varphi_i - \Psi_2) \rangle$$

Ψ_2 is the calculated reaction plane angle: $\tan n\psi_n = \dfrac{\sum_i \omega_i \sin n\varphi_i}{\sum_i \omega_i \cos n\varphi_i}, \quad n \geq 1, \quad 0 \leq \psi_n < 2\pi/n$

$$v_2\{EP\} = \frac{v_2^{obs}\{EP\}}{R} = \frac{v_2^{obs}\{EP\}}{\langle \cos 2(\Psi_2 - \Psi_R) \rangle}$$

(2) Two particle correlation method $\quad v_2\{2\} = \sqrt{\langle \cos 2(\varphi_i - \varphi_j) \rangle}$

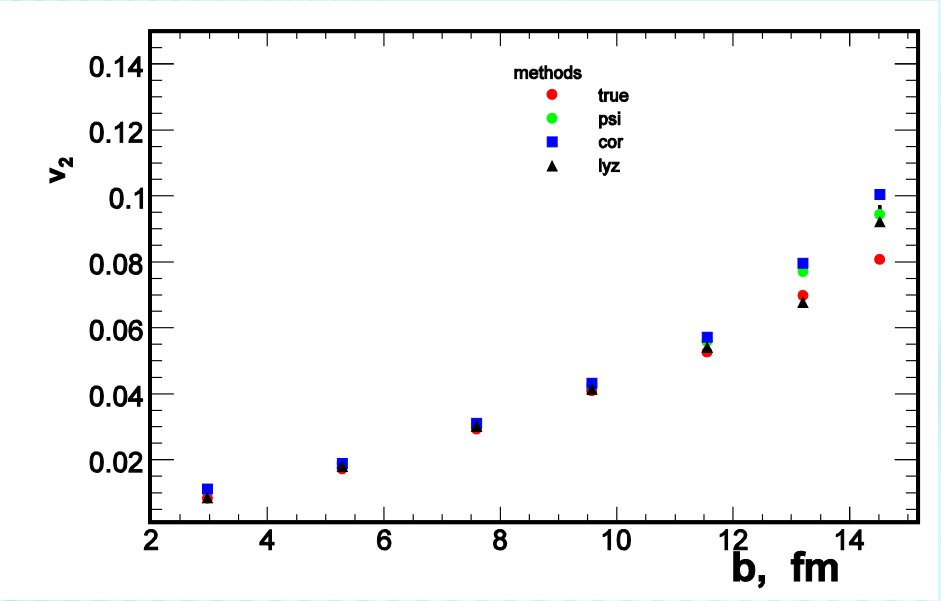
(3) Lee-Yang zero method $\quad G(ir) = \langle e^{irQ} \rangle, Q = \sum \cos(2\varphi)$

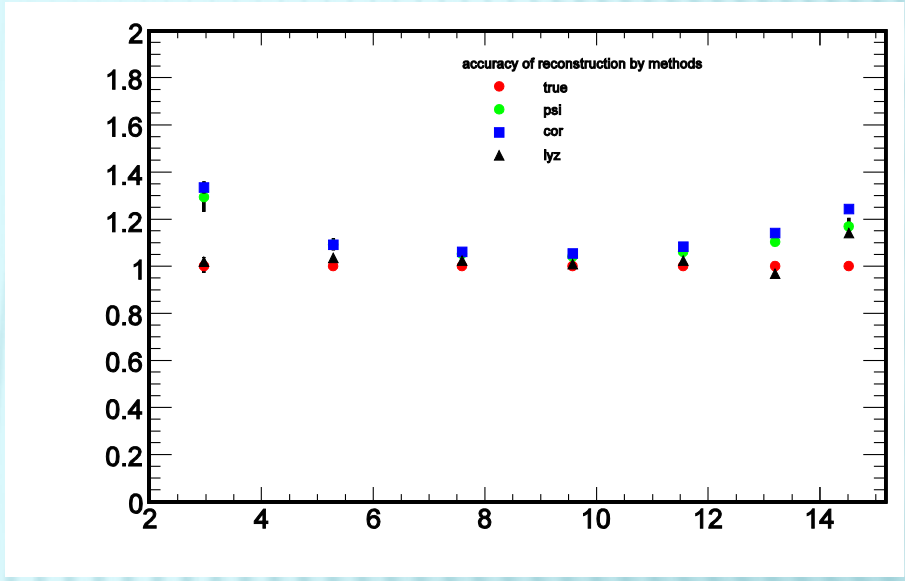
Integral v_2 is connected with the first minimum r_0 of the module of the G(ir):

$$v_2 = \frac{j_0}{Nr_0}$$

Differential flow is calculated by the formula: $\dfrac{v_2(p_T)}{Nv_2} = \mathrm{Re}\left(\dfrac{\langle \cos(2\varphi) e^{ir_0 Q} \rangle}{\langle Q e^{ir_0 Q} \rangle} \right)$

RECONSTRUCTION OF INTEGRAL VALUE OF V2 BY THE METHODS

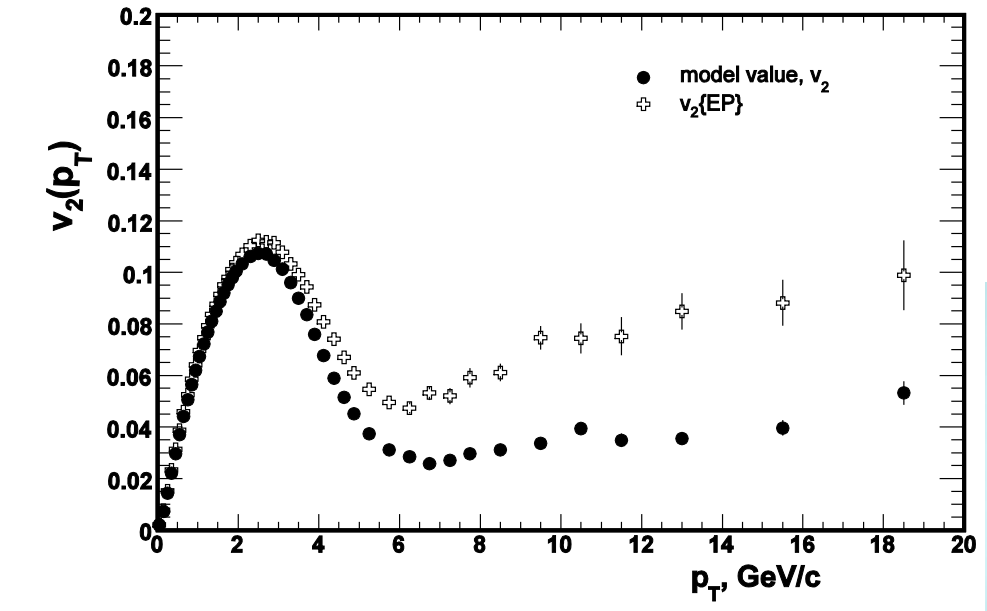


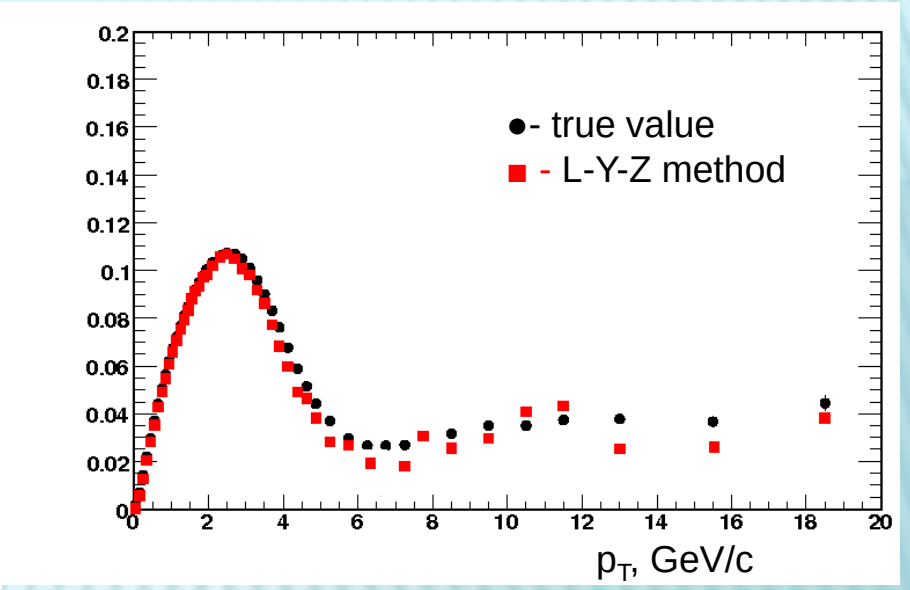


The better reconstruction is achived in midcentral collision for the methods, while Lee-Yang zero method tends to reconstruct true value at more central and more periferal collision.

Comparison of Event Plane and Lee-Yang zeroes methods (c=30%)

EventPlane method





Lee-Yang zeroes Method

Event Plane method overestimates v_2 at high p_t due to non-flow correlation (mostly because of jets).